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SETTLEMENT AND COVER SUBSIDENCE OF HAZARDOUS WASTE LANDFILLS

(FINAL REPORT)

by

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Numerical models using equations for linearly elastic deformation were developed to predict the maximum expected amount of settlement and cover subsidence and potential cracking of the cover by differential settlement in uniformly, horizontally layered hazardous waste landfills. The hazardous waste landfill models represented landfills in which unsaturated wastes were contained in steel drums that were assumed to deteriorate ultimately. The model landfill consisted of alternating layers of drummed wastes and intermediate clay cover. The maximum expected subsidence was calculated to be about 12% of the total landfill thickness. Finite element analysis of differential settlement across the landfill indicates that tensile stresses do not develop in the model case, and therefore that cracking by settlement does not occur. The findings represent only one set of conditions, however, and should not be construed as representative of landfill phenomena in general.

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ABSTRACT

Numerical models using equations for linearly elastic deformation were developed to predict the maximum expected amount of settlement and cover subsidence and potential cracking of the cover by differential settlement in uniformly, horizontally layered hazardous waste landfills. The hazardous waste landfill models represented landfills in which unsaturated wastes were contained in standard steel drums that were assumed to deteriorate ultimately in the landfill. The models were analyzed using methods of linear elasticity to estimate the maximum amount of subsidence of the final cover to be expected before and after landfill closure and after deterioration of the waste containers. The model landfill consisted of alternating layers of intermediate inert cover soils and steel drums filled with simulated waste materials. Waste drums, waste materials, and intermediate cover soils were assigned values of density, Young's modulus, and Poisson's ratio for the analysis. Landfill geometry, layer thicknesses, waste drum placement, steel drum stiffnesses, and laboratory consolidation tests on the soils and simulated wastes were also considered. To simulate postclosure waste layer deterioration, compression of the fill was calculated for decreasing values of the Young's modulus of the waste layers. The analyses indicate that as much as 92 percent of the expected subsidence of the cover is caused by closure of cavities (void space) inherent in landfilling. The maximum expected subsidence was calculated to be approximately 12 percent of the total landfill thickness. If all of the waste drums are assumed to contain 10 percent void space (a "worst case" condition) the maximum subsidence could be as high as approximately 20 percent of the fill thickness.

Finite element (FEM) analysis of differential settlement across the landfill indicates that tensile stresses do not develop, and therefore that cracking by settlement does not occur in the final cover of the landfill as modeled. Numerical and FEM models were based on data gathered for several active commercially operated hazardous waste landfill facilities in the United States. Other settlement and subsidence mechanisms, including karst and subsurface mining experiences, sanitary and low-level nuclear waste landfill experiences, and classic soil consolidation theory were addressed in addition to linear elastic deformation.

PREFACE

This study was authorized by the US Environmental Protection Agency (EPA), Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division (SHWRD), Cincinnati, Ohio, by Interagency Agreement (IAG) AD-96-F-2-A079 effective 1 April 1982, under the Project Title "Assessment of Time Settlement/Subsidence Effect on Cover Systems." Final funding was authorized in IAG WES-82-12 Amend AD-96-F-3-A079 effective 1 November 1982.

The study was conducted and the report prepared by Messrs. William L. Murphy of the Engineering Geology and Rock Mechanics Division (EGRMD) and Paul A. Gilbert of the Soil Mechanics Division (SMD), of the Geotechnical Laboratory (GL), WES. Direct supervision was provided by Mr. John H. Shamburger, Chief, Engineering Geology Applications Group (EGAG), EGRMD; Dr. Don C. Banks, Chief, EGRMD; and Dr. William F. Marcuson III, Chief, GL. Messrs. Robert E. Landreth and Robert P. Hartley, SHWRD, were EPA project officers for the study and provided guidance and assistance during the investigation. The authors acknowledge the following individuals for offering peer review of the report: Les Otte, USEPA, Cincinnati, Ohio; Dr. F. C. Townsend, University of Florida, Gainesville, Florida; Dr. N. J. Weinstein, Recon Systems, Inc., Three Bridges, New Jersey; and S. K. Banerji, University of Missouri, Columbia, Missouri.

Commander and Director of the WES during the study and preparation of the report was COL Tilford C. Creel, CE. The Technical Director was Mr. Fred R. Brown.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

RCRA	Resource Conservation and Recovery Act
FEM	Finite Element Method
PVC	Polyvinyl Chloride
ft or '	Foot or feet
V	Vertical
H	Horizontal
cm	Centimeter
sec	Second
avg	Average
pcf	Pounds per cubic foot
kg/cm^2	Kilograms per square centimeter
in.	Inch or inches
psf	Pounds per square foot
cu yd	Cubic yard
psi	Pounds per square inch
HDPE	High density polyethylene
PI	Plasticity index
LL	Liquid limit
PCB	Polychlorinated biphenyl

Symbols

H	Thickness of soil layer
e	Void ratio (volume of voids to volume of solids)
ΔH	Change in thickness
Δe	Change in void ratio
V_t	Total soil volume
p	Load on a soil mass, expressed as a pressure
C_c	Coefficient of compressibility of a soil (slope of e-log P curve)
Δp	Change in load (pressure)
t	Time
T	A time factor for computing time to achieve consolidation
H_c	Length of drainage path in a soil layer

Symbols

C_v	Coefficient of consolidation
k	Permeability
U	Degree (percent) consolidation
ϕ	Friction angle
c	Cohesion
z	Vertical axis coordinate
x	Horizontal axis coordinate
y	Horizontal axis coordinate
r	Radial axis
E	Young's modulus
E_D	Young's modulus of steel drum
E_T	Young's modulus of composite waste/soil layer
E_S	Young's modulus of intermediate cover soil layer
E_C	Young's modulus of drum contents
ν	Poisson's ratio
CH	A plastic clay
S	Subsidence
ε	Strain
σ	Stress
K_o	Coefficient of earth pressure at rest
L	Length of soil column
y	Depth within soil column
dy	Differential increment of y
γ	Unit weight
ΔL	The change in length of a soil column, or the settlement
°F	Degrees Fahrenheit
(U)	Radial deformation
K	Bulk modulus

SECTION 1

INTRODUCTION

BACKGROUND

Settlement of sanitary and low-level nuclear waste landfills with subsequent damage to or compromise of the integrity of the covers is a recognized and documented occurrence. The U. S. Environmental Protection Agency (EPA) is concerned that settlement within hazardous waste landfills may produce similar subsidence problems with cover systems. The failure or distortion of the cover system may cause consequences that are totally unacceptable to managers of hazardous waste. Little documentation exists of the extent, potential for, or mechanics of settlement/subsidence in hazardous waste landfills.

PURPOSE

This study was conducted to determine the potential for settlement of the fill and subsequent subsidence-related damage to cover systems of hazardous waste landfills and to provide information necessary for developing and improving interim and future regulatory guidance. A goal was to develop predictive numerical models to estimate the amount of subsidence and strain that would be expected to occur in the landfill and cover as a result of settlement. It was first necessary to characterize the hazardous waste landfill with respect to design, operation, and physical properties. This study has examined the characteristics of several hazardous waste landfills with special attention to those features expected to influence the potential for settlement of the fill and subsidence of the final cover. Numerical models were developed from assessment of landfill characteristics and suspected settlement/subsidence mechanisms. The potential for degradation or compromise of the final cover is examined through models developed in this report.

SCOPE

The study addresses hazardous waste landfills operating under the interim standards imposed by EPA under authority of the Resource Conservation and Recovery Act of 1976 (RCRA). The predictive models developed for the investigation are based on facilities operated by the commercial hazardous waste disposal industry. Other landfill types and subsidence mechanisms operating in geotechnical circumstances other than hazardous waste landfill situations were reviewed in developing hazardous waste landfill models, but the mechanisms and characteristics used to construct the models are those derived from an assessment of several hazardous waste landfills operating with interim status permits under RCRA.

APPROACH

The approach was to determine from the literature the known mechanisms and analytical techniques of settlement and subsidence in all geotechnical areas including mining, landfill, engineering fills, karst (geologic), tunneling and foundation investigations; to determine the mechanisms most likely to be active in a hazardous waste landfill; and to select the proper methods of analysis. A review was made of literature pertinent to settlement and subsidence in landfills. The initial computer data search used the information retrieval systems DIALOG, National Technical Information Service (NTIS), GEOREF and COMPENDEX to compile listings and abstracts of pertinent reports and documents. Review and updating of literature continued throughout the study. Site characterization, necessary for model development and problem assessment, was accomplished by contacting the hazardous waste disposal industry and through site visits to selected facilities to obtain real data on site geometry, liner and cover design and properties, waste and fill placement procedures, waste and fill physical properties, compaction efforts, leachate collection and control, subsidence experiences, and other relevant information. Sites were selected for their location, representing several areas of the nation and several climate and soil conditions; for their size, representing for the most part large facilities; and for their current activity, i.e., their status as viable commercial landfill facilities operating under RCRA guidance.

In addition, selected state agencies familiar with hazardous waste disposal in their states were contacted for further information including information about potential or existing subsidence problems, and to obtain an indication of the amount and kinds of variation in operational procedures to be expected nationwide. The authority for implementing RCRA interim standards on the state level is vested in the state Departments of Health, Water Resources Boards, special environmental regulatory commissions or departments, Natural Resources Departments, Pollution Control or Solid Waste Management Boards, or state EPA's. Some states have multiple jurisdiction for implementing the standards. The National Directory of State Agencies[1] was used to establish an initial list of contacts. Other regional or site-specific data were obtained from consulting engineeering firms and scientists and engineers of state agencies.

Numerical finite element method (FEM) models were developed for selected hazardous waste disposal situations using the data compiled in site characterization and by modifying existing FEM analytical models. The approach in the modeling analysis was to simulate worst-case conditions that would be expected in RCRA landfills, i.e., those situations producing the greatest amount of settlement. Accordingly, the larger facilities where wastes are buried in drums were used to develop the model landfill. The subsidence problem was analyzed by modeling pre- and postclosure maximum settlement in the middle of the landfill and differential settlement across the landfill.

SECTION 2

HAZARDOUS WASTE LANDFILL CHARACTERIZATION

THE DISPOSAL FACILITY

The commercial hazardous waste disposal industry has developed several variations in the design and operation of hazardous waste landfills to satisfy the requirements imposed by the implementation of RCRA. The variations nationwide are made necessary by local geologic, topographic, and hydrologic conditions, state requirements that may differ from Federal guidelines, individual preferences by the waste disposer, and the demand placed on particular facilities by producers of hazardous wastes. Nevertheless, a typical or "generic" landfill can be said to possess all or most of the following characteristics:

a. Pits (cells) are excavated in native soil or rock of low permeability (aboveground facilities enclosed by soil embankments are less common).

b. Single- or multicell construction is practiced, the cells isolated by berms and the multicell groups isolated by berms, liners, and covers.

c. Depths are commonly 15-50 ft, but may be as great as 100 ft.

d. The base of the cell is above the water table or aquifer.

e. Cells are lined with single or multiple natural or synthetic barriers with very low permeability to water (10^{-7} to 10^{-8} cm/sec).

f. Cells are equipped with leachate collection and monitoring system.

g. A final cover (cap) of synthetic and/or natural materials is installed.

h. Wastes are placed with some care in layers generally 3 ft thick or less and covered with less than 2 ft of crushed rock or soil fill (intermediate cover)*. The waste and intermediate cover are alternated as the cell is filled.

i. Compaction of liners and caps is usually controlled and monitored; compaction of waste and fill is limited and is that obtained by passage of tracked and wheeled waste placement vehicles.

j. Final cover caps of closed cells are grassed and may be equipped with settlement plates for subsidence monitoring.

k. Operators are required to solidify all liquids enclosed within the cell (no free liquids permitted).

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* Throughout this report "intermediate cover" refers to the inert fill layer placed over a waste layer as the cell is filled. "Final cover" refers to the uppermost cap of the cell that provides permanent closure of the cell.

The characteristics are discussed further in the following paragraphs. Appendix A describes in detail the characteristics of hazardous waste landfills for which information was gathered for this study. Some, but not all, landfill construction, filling, and capping procedures were observed firsthand by the authors. The landfills described are believed to represent modern controlled waste disposal facilities operating under RCRA. They do not represent the entire range of closed hazardous waste landfills nationwide. The practices found, and discussed here, do not necessarily comply with RCRA guidance.

Figure 1 illustrates a generic RCRA controlled hazardous waste disposal landfill in plan and profile. Figure 1 is a composite of many proposed and existing designs all of which meet current RCRA requirements for long-term containment and isolation of hazardous wastes. There are active facilities of simpler and more complex design than that shown in Figure 1. RCRA guidelines[2,3] are interim. State and local controlling government agencies and industry interpret or meet the implied requirements in various ways. Accordingly, facility design and operation vary regionally and/or within the industry.

THE CELL LINER

Cells commonly are placed below ground level in pits (often called trenches), excavated in soil or rock of relatively low permeability, such as clays or claystones. Aboveground landfills (impoundments) are also used but are less common. Some areas are experiencing decreasing availability of landfill acreage and will soon begin adding wastes atop existing, filled hazardous waste landfills. Pits and trenches are apparently preferred by the industry for their simplicity of construction and less critical stability design requirements. Common practice is to require a site with a deep water table overlain by a sufficient thickness of low permeability soil or rock. The base of the cell is usually graded to slope toward a leachate collection sump and monitoring well. Typical leachate collection systems are perforated PVC pipe covered by granular fill. Graded filter design criteria were not observed in the typical leachate collection systems. Leachate collection systems commonly are emplaced only along the base of the cell. At least one facility contacted, however, also installed a vertical drainage system around

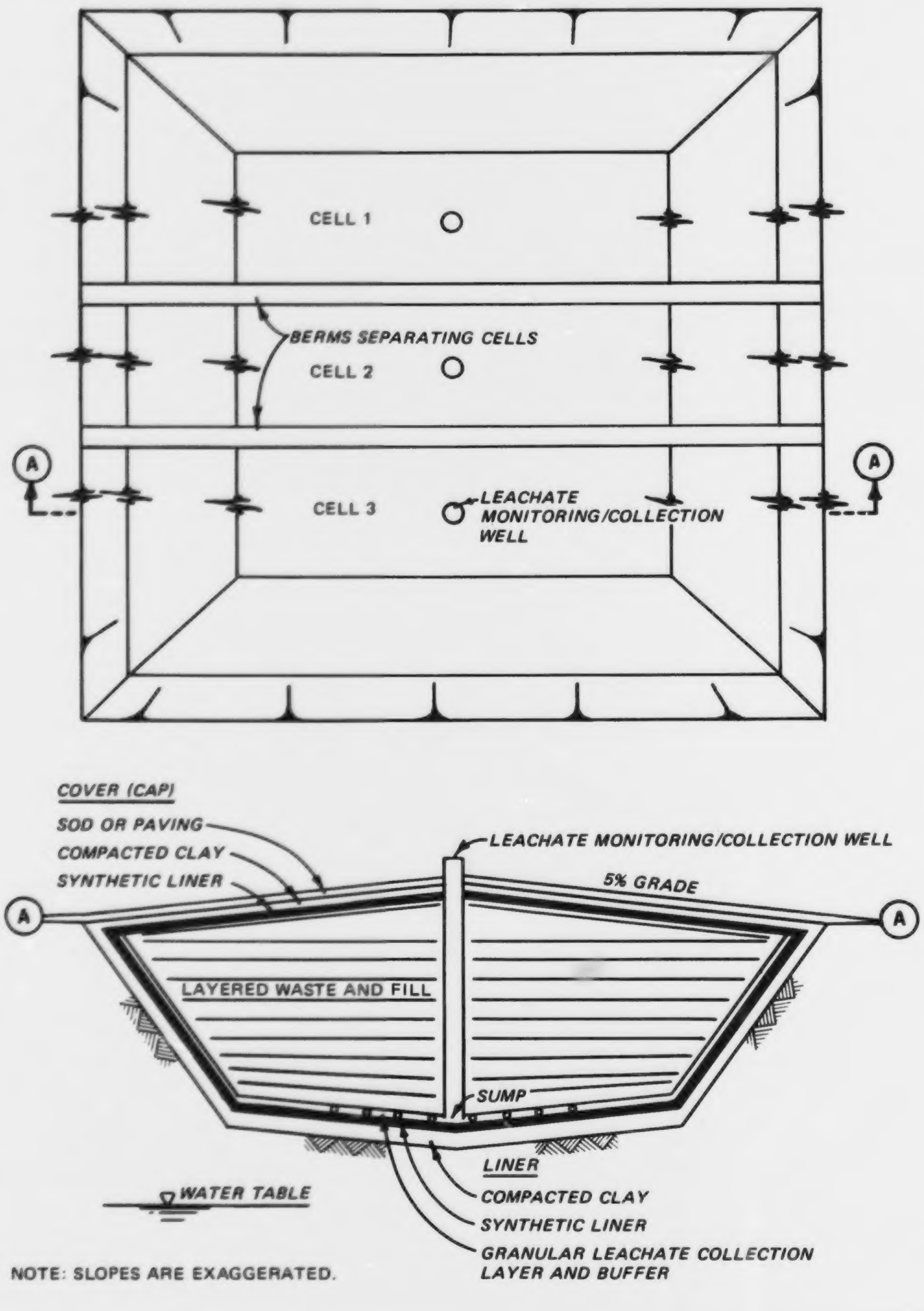
CELL 1
BERMS SEPARATING CELLS
CELL 2
A
A
CELL 3
LEACHATE MONITORING/COLLECTION WELL
COVER (CAP)
SOD OR PAVING
COMPACTED CLAY
SYNTHETIC LINER
LEACHATE MONITORING/COLLECTION WELL
5% GRADE
A
A
LAYERED WASTE AND FILL
SUMP
LINER
COMPACTED CLAY
SYNTHETIC LINER
GRANULAR LEACHATE COLLECTION LAYER AND BUFFER
WATER TABLE
NOTE: SLOPES ARE EXAGGERATED.

Figure 1. Generic RCRA controlled hazardous waste disposal landfill (see text).

the cell riser or standpipe. Compound liners (clay plus a geomembrane*) encase the cells along the base and sides and may be joined with the cover liner at closure. The compound liner commonly is a combination of a clay barrier and one or more synthetic liners such as polyethylene, PVC or other geomembrane of 30 to 100 mil thickness. One-piece liners consisting of a thick clay layer or in-place clay-rich soil with no synthetic liner are also used and in fact were prevalent in the facilities visited for this study. A layer of sandy soil or gravel may be laid down atop the liner below the first layer of waste to serve as a buffer protecting the liner from waste placement operations and to convey leachate to the leachate collection sump. Clay liners are compacted with sheepsfoot rollers in lifts to a specified density, to a specified laboratory measured permeability to water, or to a density corresponding to a particular permeability. The specified density commonly represents a moisture content wet of optimum (optimum moisture content of a laboratory soil compaction test). A vibratory roller is used by at least one operator on the final lift to form a smooth surface on which to place the synthetic liner.

WASTE PLACEMENT AND CELL FILL

Hazardous wastes being considered for land disposal and pertinent to this study possess characteristics of ignitability, toxicity, reactivity or corrosivity. Nuclear waste depositories are excluded from consideration as hazardous waste fills. Waste chemistry is considered to be of only secondary importance, and waste containment method and waste placement characteristics of primary importance, to the subject of this study, i.e., landfill settlement and cover subsidence.

Wastes are emplaced primarily in steel 55-gallon drums and in bulk form. Plastic drums and steel 85-gallon "overpack" containers, large drums containing leaking or damaged 55-gallon containers for transportation to the facility, are present in lesser amounts. Miscellaneous wastes such as plastic sheeting, wooden pallets, crushed drums and other containers occupy a smaller percentage of the cell fill. Some facilities segregate wastes on the basis of, for example, acidity, alkalinity, organic content, ignitability and toxicity by placing barrier berms between cells or between sections within cells. Drums are usually emplaced closely together in a part of the waste layer or may constitute an entire layer. Drums are placed either on end or on their sides, the choice being more a matter of preference by the site manager than of established advantage of one method over the other. However, all drums at a given facility are placed in the same orientation. One state waste disposal controlling agency reported the practice of isolating "soluble" (deteriorating) wastes in separate cells so that all expected settlement occurs in a predetermined location. Soluble wastes would include drums. Other sites handling predominantly bulk wastes distribute the "soluble" type of waste containers and debris throughout the fill to minimize the effects.

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* A geomembrane is a synthetic impermeable liner material that may be a prefabricated polymer such as rubber or plastic or a sprayed-on emulsion such as asphalt[4].

To satisfy the general RCRA requirement that no free liquids be enclosed within the disposal cell, liquids must be solidified before burial. Bulk liquids, for example those delivered by tank truck, are commonly impounded behind temporary dikes in one part of the cell and "solidified" in place with local soil, fly ash, fuller's earth, or other material before being covered. Drummed liquids are either solidified in the drum by the addition of absorbent filler to the drum, or are decanted and solidified within the cell. Air or void space within the drum is also minimized by addition of filler or by crushing empty drums. Rain water entering the cell during filling operations is solidified in the same manner as bulk liquids or is pumped out to temporary onsite evaporation ponds. The thickness of waste layers is generally equal to the length or diameter of a waste drum. Each layer of waste is covered with a layer of dry crushed rock, soil, or other material spread by tracked or wheeled vehicles. Some attempt is made to distribute the intermediate cover material into voids around and between drums. The intermediate cover may be specially selected material chosen for its absorbency, neutralization effects, or nonflammability, or reworked, crushed rock or soil stockpiled during cell excavation. One waste disposal firm listed six types of daily (intermediate) cover that it uses within a single facility, the choice of material satisfying the specific requirements, such as ignitability or alkalinity, of the particular waste being covered. Waste and intermediate cover layers are alternated as the cell is filled and then a final cover is installed. Those facilities in which most of the wastes are in dry or solidified bulk form do not use an intermediate cover during filling operations.

CELL COVER

Design of the final cover varies. The cover typically has the following layers: (a) a buffer layer consisting of local soils or intermediate cover materials which protects the barrier from the uppermost waste layer and (b) synthetic liners similar to those of the cell liner. The central part of the filled cell or of the final cover is elevated so that the final cover surface slopes away on at least a 5 percent grade, and grades as high as 8 percent were reported (Figure 1). Lutton et al.[5] suggested 3 to 5 percent as quoted for use in grounds maintenance. Some facility operators and regulatory officials stated that the final cover surface is mounded high enough to maintain sufficient grade after expected or potential settlement of the final cover. The Draft RCRA Guidance Document for Landfill Design, Liner Systems and Final Cover, issued July 1982, suggested that the final cover slope be a minimum of 3 percent to prevent ponding, and no greater than 5 percent to prevent excessive erosion. There appear to be no data on percentage or amount of settlement to expect in a hazardous waste landfill and presumably the final cover height is based on intuition by operators and regulatory personnel (Sections 4 and 5 of this report suggest means by which settlement (subsidence) can be predicted for modeled hazardous waste landfills). The surface is vegetated to prevent erosion of the final cover materials. Compaction efforts and control for the final clay cover barrier are similar to those for the cell liner. Settlement plates may be installed on closed cells for monitoring of subsidence, but none were emplaced at sites contacted in this study.

Lutton et al.[5] presented guidelines and suggested criteria for construction of solid waste landfill final covers. Layering of final cover materials was suggested to meet the logical requirements of a landfill final cover to:

- a. Vent gases generated within the cell.
- b. Isolate wastes from contact with the environment by means of a barrier.
- c. Drain water off the fill to prevent infiltration and ponding.
- d. Protect the barrier layer(s) from damage by wastes or construction activities.
- e. Prevent erosion of the final cover soils.

The EPA guidance document suggests that the final cover should consist of three layers. The bottom layer overlying the topmost waste layer should be a two-component low permeability layer. The upper component of the bottom layer should below the frost penetration depth and should consist of at least 20-mil synthetic membrane protected above and below by at least 6 in. of bedding material no coarser than sand. The lower component should consist of at least 24 in. of soil compacted in 6-in. lifts to achieve a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec. The middle layer of the final cover serves as drainage and should be at least 12 in. thick, have a hydraulic conductivity of at least 1 x 10^{-3} cm/sec, and should be overlain by a graded granular filter or synthetic fabric filter. The top cover layer should be soil at least 24 in. thick and capable of supporting shallow-rooted vegetation that will effectively minimize erosion. Variations of the suggested final cover scheme in actual practice by the hazardous waste disposal industry ranges from a final cover consisting of a single thick clay layer to a multilayered cap of clay and polymeric membrane barriers, sand drainage blanket and gas-venting layer. At least one state regulatory agency requires an additional soil layer equal in thickness to the local freeze-penetration depth to further protect the final cover materials.

QUALITY CONTROL

The RCRA controlled commercial hazardous disposal waste facilities maintain a technical staff onsite or in a regional office, or contract to consulting engineering laboratories, for cell design, barrier compaction design and permeability control, monitoring of leachate quality and migration, and waste analysis.

SECTION 3

SUBSIDENCE MECHANISMS AND RELATED PROBLEMS

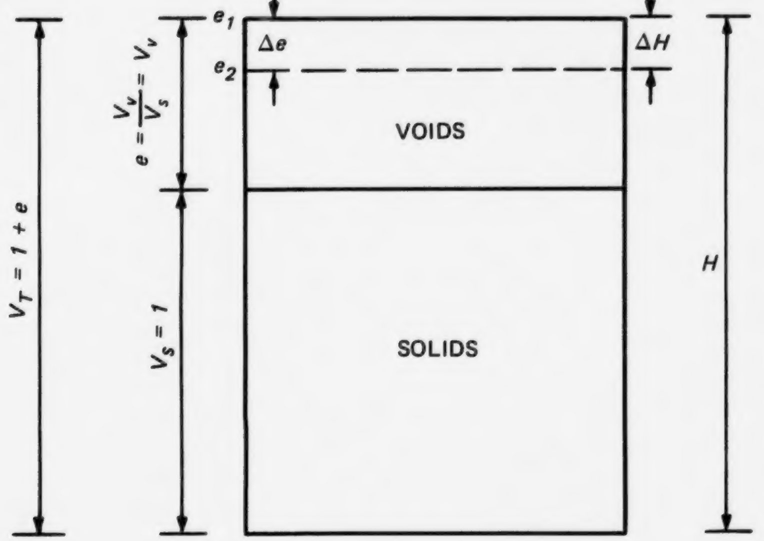
INTRODUCTION

Section 3 discusses mechanisms by which settlement of materials and/or subsidence of the surface occurs. The discussion includes all conditions, both natural and artificial, that have been recognized to cause settlement and subsidence. Such conditions are consolidation and compressibility, commonly investigated in connection with soils; cavity-related conditions encountered in natural karst regions and in underground mining and tunneling; and a variety of mechanisms identified and documented for sanitary and low-level nuclear waste landfills. The purpose of Section 3 is to address known settlement/subsidence mechanisms, evaluate them, and select the proper mechanisms for analysis of settlement/subsidence in hazardous waste landfills. The discussion of consolidation of soils is addressed again in Sections 4 and 5 concerning analysis of settlement attributed to layers of soil and waste in hazardous waste landfills. Settlements induced by seismic events are not considered.

SUBSIDENCE BY CONSOLIDATION

Primary Consolidation

Consolidation of a soil is the decrease in void ratio (volume of voids to volume of solids) by expulsion of fluids from the voids under excess hydrostatic pore pressure (primary consolidation) and by deformation of the skeleton of the soil mass and compression of gases in the voids (secondary compression). The decrease in void ratio by consolidation represents a decrease in volume of the soil mass and can cause the surface of the mass to subside. The classic Terzaghi theory for one-dimensional consolidation of a soil assumes that deformation of the soil mass is by change in volume by the expulsion of water from the voids and that the soil is saturated (there are also several other important assumptions, for example, see Means and Parcher, p. 208.[6] The change in void ratio of a soil is a measure of consolidation. If a mass of soil (Figure 2) is compressed, the change in its thickness ΔH can be expressed as a change in the void ratio (Δe).



$V_T = 1 + e$
$e = \frac{V_v}{V_s} = V_v$
$V_s = 1$
e_1
e_2
Δe
ΔH
VOIDS
SOLIDS
H

Figure 2. Relation of thickness (H), volume (V_t) and void ratio (e) of a soil.

The unit deformation is

$$\frac{\Delta e}{V_t} = \frac{\Delta e}{1 + e} \quad \text{(see Figure 2)} \tag{1}$$

where V_t = total soil volume and e is the initial void ratio. Since ΔH can be expressed as Δe, and V_t as H (Figure 2)

$$\frac{\Delta H}{H} = \frac{\Delta e}{1 + e} \tag{2}$$

where H is the total thickness of the soil mass, and the amount of settlement due to consolidation is then

$$\Delta H = H \frac{\Delta e}{1 + e} \tag{3}$$

An estimate of the amount of settlement to be expected in a soil subjected to a load in the field can be made from laboratory consolidation tests on representative soil samples and field loading and overburden thickness data. The laboratory consolidation test yields a curve of change in void ratio (e) with increasing load (p). The slope of the resulting e-log p curve is called the coefficient of compressibility (C_c), and is expressed as

$$C_c = \frac{e_1 - e_2}{\log p_2 - \log p_1} = \frac{\Delta e}{\Delta \log p} \tag{4}$$

where p_1 and p_2 define one log cycle of pressure for the change in void ratio ($e_1 - e_2$).

Substituting for Δe in Equation 3,

$$\Delta H = H \frac{C_c}{1 + e} \Delta \log p = H \frac{C_c}{1 + e} (\log p_2 - \log p_1)$$

and since $p_2 = p_1 + \Delta p$,

$$\Delta H = H \frac{C_c}{1 + e} \left[\log (p_1 + \Delta p) - \log p_1 \right]$$

$$= H \frac{C_c}{1 + e} \log \frac{p_1 + \Delta p}{p_1}$$

or settlement

$$\Delta H = H \frac{C_c}{1 + e} \log \left(1 + \frac{\Delta p}{p_1}\right) \tag{5}$$

Equation 5 predicts the amount of settlement to be expected by one-dimensional primary consolidation of a saturated soil mass of thickness H, initial void ratio e, initial overburden stress p_1, and compressibility C_c when loaded at an increase in stress of Δp, assuming Terzaghi's assumptions are met.

The rate of settlement, or change in soil volume with time, can be predicted for selected degrees of consolidation (percent consolidation) with the equation

$$t = \frac{T\ Hc^2}{c_v} \tag{6}$$

where

t = time to achieve average percent consolidation (U)

T = a time factor, for which a table is available relating T and U (see Ledbetter)[7]

Hc = length of drainage path for expulsion of water from the soil voids (for single drainage, as with soil overlying an impervious barrier, $Hc = H$; for double drainage, as with soil bounded above and below by pervious zones, $Hc = H/2$; for multiple drainage path, as with soil interspersed with alternate layers of pervious zones, Hc = fraction of H)

c_v = coefficient of consolidation, a laboratory determined value dependent upon the soil's compressibility (C_c), its permeability (k), and the void ratio (e)

Conversely, the degree (percent) of consolidation (U) that will occur at an elapsed time t can be predicted by solving for T in Equation 6, and then referring to the table (T vs U) for U .

Consolidation of soils by lowering of the water table has been identified as a possible cause of ground subsidence in some locations[8,9,10,11]. The effect of lowering the water table in a soil is to surcharge the soil by increasing the effective stress through a decrease in pore pressure. The soil consolidates following Terzaghi's one-dimensional consolidation theory. Fang and Cleary[12] discuss consolidation by ground water lowering for coarse- and fine-grained soils in confined and unconfined aquifers.

Secondary Compression

Similar calculations can be made for settlement from secondary compression (deformation of the soil mass), which occurs sometime after primary consolidation as most of the applied stress is transferred to the soil skeleton, by considering the laboratory determined coefficient of secondary compression. Total settlement is the sum of the primary consolidation and secondary compression settlements. If the loading is not instantaneous, but instead is applied gradually as in the case of extended construction time, time factor curves[7] are consulted for modified values of T and U. An example of settlement calculations for a layered saturated sludge landfill is presented in reference 7, pp 28-33.

Primary consolidation is not expected to be the dominant mechanism for settlement of hazardous waste landfills. Regulations prohibiting the placement of free liquids in landfills, the use of leachate collection and removal systems, and the use of liquid-absorbing stabilizing agents limit saturation of the waste fill. Primary consolidation may occur initially, during filling, before closure but long-term settlement should be analyzed on the basis of deformation of the waste layers and deteriorating waste containers.

CAVITY-RELATED SUBSIDENCE

The presence of large voids, herein called cavities, within a soil or rock mass has been recognized as a cause of subsidence of the ground surface. Analyses of cavity-related subsidence have been made in relation to mining[12,13,14,15,16,17] natural karst (solution cavity) areas[8,15,18], and landfills[9,19,20]. The relevance of subsidence mechanisms identified in karst and mining studies to analysis of cavity-related problems in hazardous waste disposal fills is examined in this section. Hazardous waste disposal facilities can contain initially rigid but ultimately collapsible containers that are placed in various geometries (horizontally, vertically, and layered with soils). They may contain highly compressible materials and their rigidity may initially inhibit pre- and postclosure deformation of the fill. This section discusses cavity-related subsidence mechanisms recognized in karst and mining investigations and outlines subsidence investigative techniques developed for their analysis.

Mining Subsidence Mechanisms

Discussions of mining subsidence have generally consisted of describing the geometry and size of the surface subsidence trough in terms of the size and depth of the mined-out zone associated with the trough. Some limited attempts have been made[12,15,21] to explain the failure mechanisms. Brink[15], for example, recognizes closure of the mined opening as a mechanism leading to surface subsidence. He attributes the closure to movement of the overburden into the mined opening either en bloc or differentially. En bloc movement of rock above the opening occurs if the arch or dome of fracturing above the mined opening does not extend to the surface (the mined opening is deep). Differential movement (Brink's "macroplastic") occurs if the fracturing extends to the surface (the mined opening is shallow), and downward movement of overlying rock and soil is by slippage along fracture planes. Attewell and Farmer[15] describe the subsidence trough in terms of an active wedge. Brauner[14] described subsidence as continuous if a regular subsidence trough was formed, or discontinuous if movement occurred along fractures or in collapse pits (sinkholes). Other studies of subsidence in mined areas are empirical, apply to specific geologic/ geographic environments, and describe the geometries rather than explain the mechanisms of subsidence features (for example, references 13 and 16).

Mining subsidence investigations have been conducted in response to potential or real damage to buildings and utilities in a mining area and accordingly address the parameters of slope and curvature of the subsidence trough, horizontal strains and displacements, and maximum subsidence. Figure 3 diagrams the descriptive geometry commonly used in mining subsidence investigations (Figure 3 is derived from references 14 and 16). The limits of the subsidence trough, which is not drawn to scale relative to the mined opening, are defined by the "draw" line constructed from the edge of the mined opening to the surface. Attewell and Farmer[21] depict the vertical angle of the draw as $45-(\phi/2)°$, which defines a theoretical active wedge with ϕ the effective friction angle of the soil or rock above the opening and with the principal stress acting vertically. Maximum strains at the subsided ground surface occur at points of maximum curvature on the subsidence curve, or trough. The strain is a minimum and the horizontal displacement a maximum at the inflection points and the horizontal displacement is minimum at the center of the trough (see Figure 3).

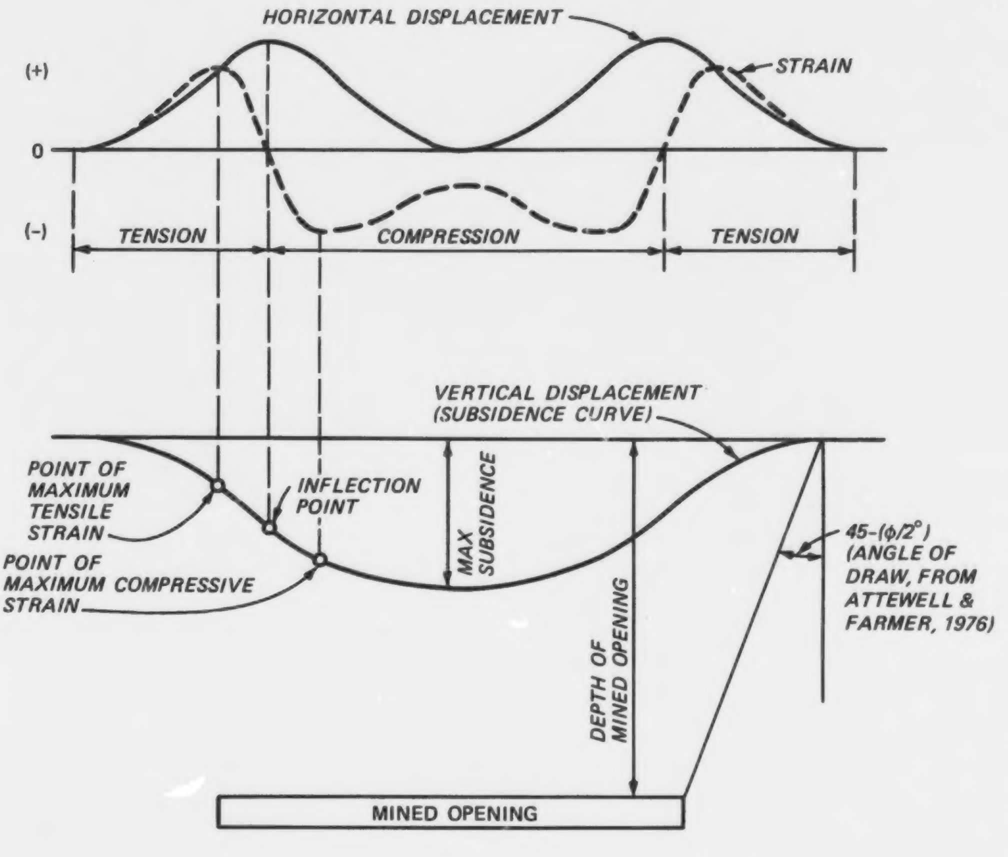

HORIZONTAL DISPLACEMENT
STRAIN
(+)
0
(-)
TENSION
COMPRESSION
TENSION
VERTICAL DISPLACEMENT
(SUBSIDENCE CURVE)
POINT OF MAXIMUM TENSILE STRAIN
INFLECTION POINT
POINT OF MAXIMUM COMPRESSIVE STRAIN
MAX SUBSIDENCE
DEPTH OF MINED OPENING
45-(φ/2°) (ANGLE OF DRAW, FROM ATTEWELL & FARMER, 1976)
MINED OPENING

Figure 3. Descriptive geometry of mining subsidence investigations.

Brauner[14] attributes damage to surface structures to the slope, curvature, horizontal displacement, and resultant strain in a subsidence trough. Following Brauner, slope of the trough is the change in subsidence (vertical displacement) with respect to the horizontal reference axis. Slope-induced damage commonly takes the form of change in gradient of surfaces, utility pipelines, and drainage. Curvature is approximately equal to the derivative or rate of change of the slope and is produced by differential vertical movement of the surface. Curvature-induced damage is caused by shear strain (or angular distortion) and bending. Differential horizontal displacement distorts alignments of structures on the surface.

Karst Subsidence

Definition and Significance. Karst describes a terrain characterized by closed depressions (sinkholes), caves and underground drainage. Karst occurs in and overlying deposits of water-soluble rock such as limestone and is attributed to subsurface solution and erosion of the rock. Ground subsidence in karst terrains has been documented extensively in the United States[18,22], in South Africa[8,15], and in Europe[23]. Sinkholes and depressions are the surface expressions of the solution channels and caverns formed underground in the soluble rock. Formation of the sinkholes and depressions in karst terrain can be a process of collapse of the cavern roof, of piping of overburden soils into the cavern by downward percolating water, of collapse of the overburden arch or bridge spanning a cavern or of sagging of stratified materials into the cavity. Settlement within the overburden soils overlying cavernous rock in karst terrains presents a convenient field and laboratory tested model of cavity-related subsidence mechanisms useful in developing analyses of subsidence in waste landfills where the potential for cavities exists. The geologic and hydrologic processes responsible for development of the soluble rock caverns and solution channels of karst is less analogous. Accordingly the mechanisms responsible for the formation of sinkholes are discussed below.

Mechanisms of Sinkhole Development. A sinkhole is defined in this report as a closed surface depression originating at depth in a cavity or locally highly compressible zone. The sinkhole represents local subsidence or collapse of the ground surface. Field and laboratory observations of karst features recognize three mechanisms of sinkhole development[8,15,18]: piping, sagging, and arch collapse. Piping is the erosion of cohesionless or low cohesion soils through channels or slots (pipes) by water percolating down gradient toward a base level, such as the water table. The soil erodes from the mouth of the pipe or slot, the erosion progressing upwards by a process of headward piping[15]. Piping can form sinkholes if a sufficiently large cavern exists below the slot to accept the eroded material and if sufficient water is available for transport of eroded soil. Sowers[18] applies the term "ravelling" to piping erosion phenomena.

Sagging occurs in horizontally layered soils overlying a cavity if the span of the roof of the cavity is greater than a critical value which is determined by the strength of the soils[8]. Figure 4 illustrates documented sagging of horizontally layered rock and soil units overlying a solution cavity. The situation depicted in Figure 4 might be expressed by a surface depression but would not form a collapse sinkhole unless failure or headward erosion (piping) of the units overlying the cavern occurred. The tendency of the overlying layers to sag and the amount of sag will depend primarily on the cohesion or bond strength of the material in the layers. The situation of horizontal layers spanning a void can be represented by a simple beam supported at each end and subject to a uniformly distributed load (gravity), as illustrated in Figure 5a. The tendency of the beam to sag is explained by analyzing the shear and bending moment diagrams (Figures 5b and 5c, respectively). The shear stress is greatest at the supports (beam ends) and decreases linearly away from the ends to zero at the center (Figure 5b). The bending moment, however, is a maximum at the center of the beam (Figure 5c). The lower surface of the beam at the center is placed in tension by the moment and if the moment at the center of the span is great enough to set up tensile forces exceeding the cohesive strength of the beam material the beam will yield, or sag. If the span is less than the critical distance arching of stresses may occur in the beam and the beam will not deflect.

Arching is the bridging of a cavity by overburden soils by the transfer of load in the overburden to the sides or abutments of the cavity opening. Terzaghi and Peck[26] used a simple laboratory test to explain the phenomenon of arching. Figure 6 illustrates the test which consists of a layer of sand placed on a platform containing a trapdoor overlying a cavity (AB in Figure 6a). Pressure on the platform and door is measured on a scale. Figure 6b shows the

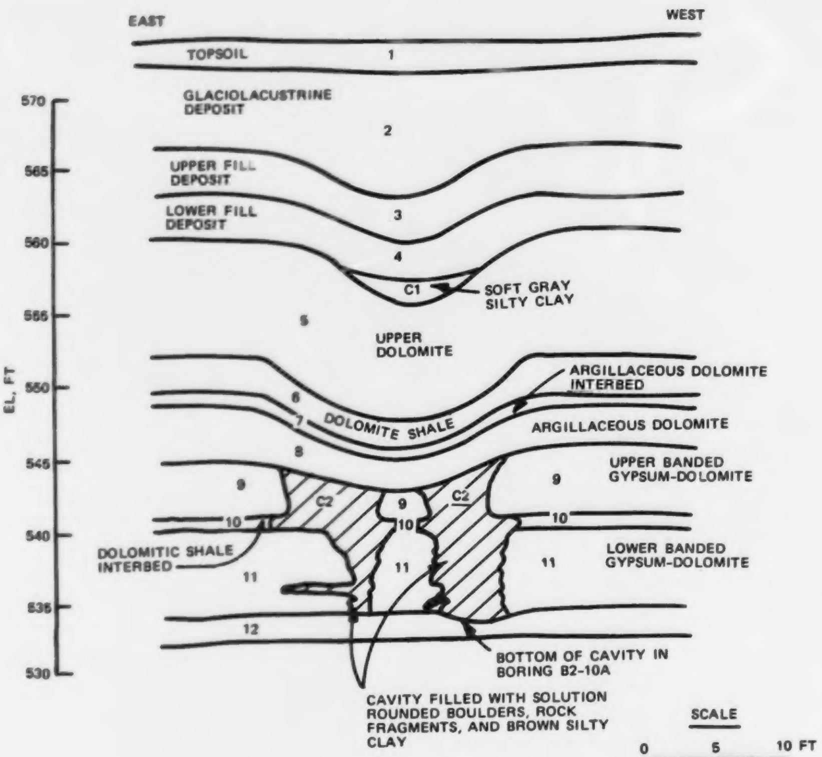

EAST
WEST
TOPSOIL
1
GLACIOLACUSTRINE DEPOSIT
2
UPPER FILL DEPOSIT
3
LOWER FILL DEPOSIT
4
C1
SOFT GRAY SILTY CLAY
5
UPPER DOLOMITE
ARGILLACEOUS DOLOMITE INTERBED
6
7
DOLOMITE SHALE
ARGILLACEOUS DOLOMITE
8
UPPER BANDED GYPSUM-DOLOMITE
9
C2
10
DOLOMITIC SHALE INTERBED
11
LOWER BANDED GYPSUM-DOLOMITE
12
BOTTOM OF CAVITY IN BORING B2-10A
CAVITY FILLED WITH SOLUTION ROUNDED BOULDERS, ROCK FRAGMENTS, AND BROWN SILTY CLAY
EL, FT
570
565
560
555
550
545
540
535
530
SCALE
0
5
10 FT

Figure 4. Sagging of horizontal strata overlying solution cavity (reference 24).

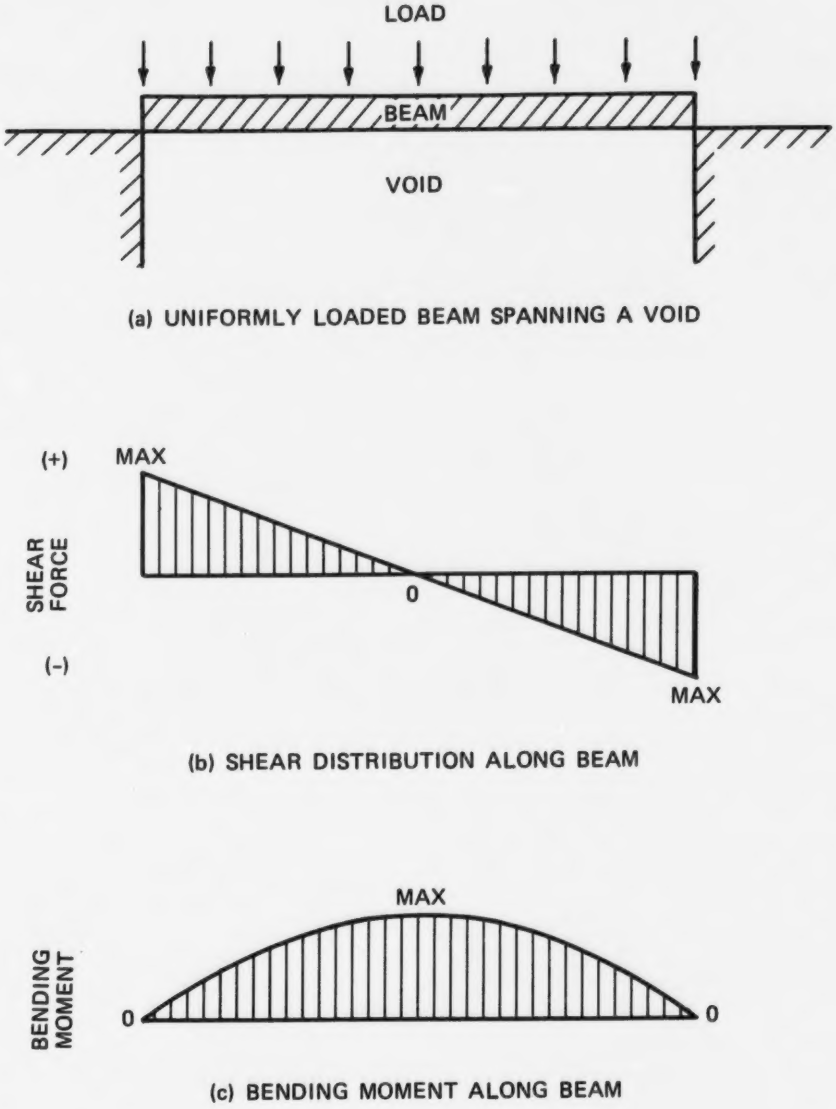
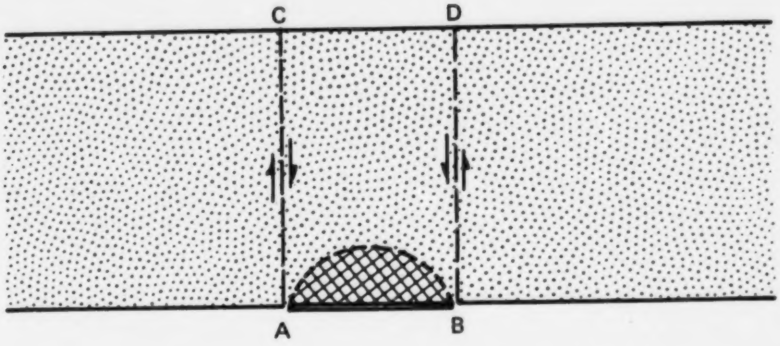
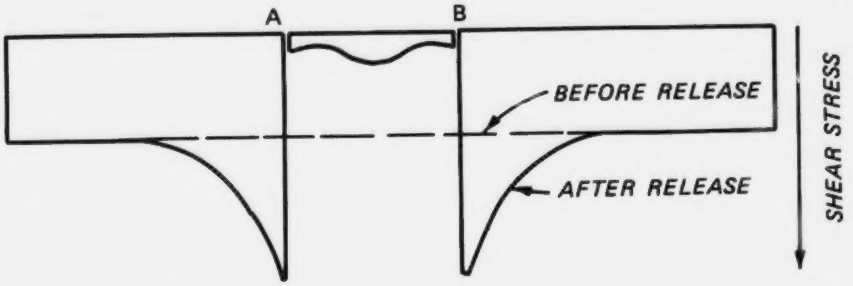

LOAD
BEAM
VOID
(a) UNIFORMLY LOADED BEAM SPANNING A VOID
(+)
MAX
SHEAR FORCE
0
(-)
MAX
(b) SHEAR DISTRIBUTION ALONG BEAM
MAX
BENDING MOMENT
0
0
(c) BENDING MOMENT ALONG BEAM

Figure 5. Stresses on beam spanning a void (modified after reference 25).



(a) LAYER OF SAND ON PLATFORM WITH TRAPDOOR AB



(b) STRESS (PRESSURE) DISTRIBUTION ON PLATFORM AND RELEASED TRAP DOOR

Figure 6. Test illustrating arching in soil over a cavity (after reference 26).

pressure distribution after allowing the trapdoor to yield under the weight of sand. The shear forces (pressure) on the abutments (A,B) are large and those on the door small, a force distribution analogous to that of the beam in Figure 5b. The reason is that the central column of sand above the trapdoor is resisted by shear stresses along its boundaries (AC and BD in Figure 6a). Terzaghi and Peck further state that the ultimate pressure on the released trapdoor does not exceed the weight of a mass of sand having the arch shape of the shaded zone in Figure 6a, regardless of the height of the column of sand. (Coates[27]) showed that the pressure on the trapdoor is equal to a column of ground equal in height to the radius of the trapdoor.) If the sand has some cohesion the trapdoor can be removed and the sand will bridge the gap and not fall through. The pressure not carried by the trapdoor is supported by arching action into the abutments.

Arch failure in overburden soils in karst terrain has been identified as a major cause of sinkhole development by several authors[8,15,18]. Figure 7 illustrates the typical karst field conditions necessary for sinkhole development by progressive arch failure. Solution along joints and bedding planes and in more soluble strata within the rock of Figure 7 has created caverns and slots. The rock is overlain by a residuum of insoluble material and other soils. Piping of soils clogging the slot by percolating water in Figure 7a has progressed upward to the base of the residuum where an arched cavity (a dome in three dimensions) has been created. Progressive failure of the arch proceeds as shown by the dashed lines and arrows in Figure 7a until a stable configuration is achieved, which may be an open-roofed sinkhole like that shown in Figure 7b. The eroded collapse debris accumulates in the cavern below or, if sufficient discharge and gradient are available in the percolating water, is carried out of the system.

Jennings[8] and Brink[15] observed karst subsidence in the field and identified the requirements for sinkhole development:

a. Rigid abutments must exist to allow an arch to form by the process of stress transfer (discussed above). A condition of arching must form in the residuum between the abutments; if the span between abutments is too great, arching cannot occur.

b. A cavity must develop in the residuum below the arch. The initial cavity can be produced by piping as explained above.

c. A reservoir has to exist below the arch to accept material removed as the arch enlarges. If collapse material is not removed the

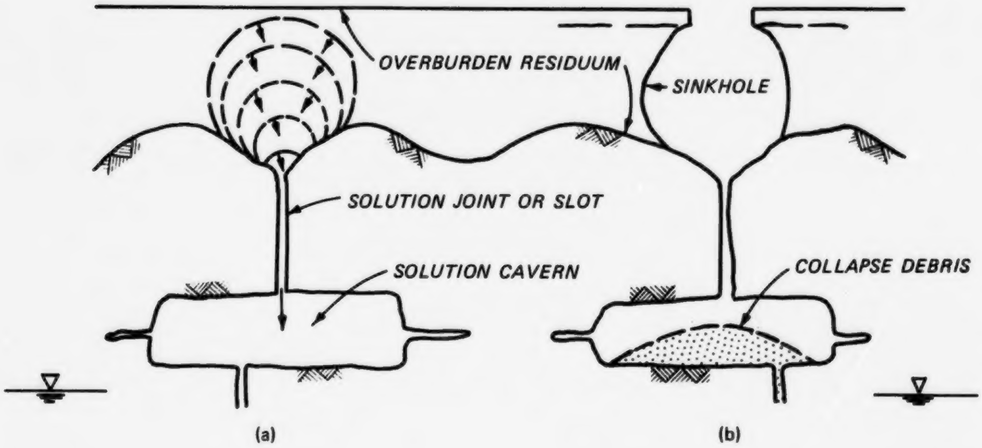

OVERBURDEN RESIDUUM
SINKHOLE
SOLUTION JOINT OR SLOT
SOLUTION CAVERN
COLLAPSE DEBRIS
(a)
(b)

Figure 7. Sinkhole development by arching in karst terrain (modified from reference 15).

boundaries of the arch may stabilize and the arch cease to grow. Arch progression and stabilization is discussed further, below.

d. Once an arched cavity has been established in the residuum, a triggering mechanism must occur to render the arch unstable. The most common triggering mechanism is percolating water migrating toward the water table. Dynamic mechanisms, such as earth tremors, vibratory loading by vehicles at the surface, and mining activity have also been identified.

Water that enters the soils of the arch decreases the capillary tension between soil grains that is responsible for the cohesive strength of the arch[18]. If the gradient and flow are high enough the percolating water may also erode soils from the arch surface. Moving water also carries away collapse debris that collects at the base of the arch and thereby produces instability in the arch.

The mechanics of arch failure in soil were analyzed by Lobban (reported in reference 8) who used a finite difference analogy of a soil-filled bin equipped with a trapdoor. Lobban's model calculated and displayed the stress trajectories and zones of overstress for the bin with yielding trapdoor for soils of different cohesions and shear strengths and for different boundary conditions. Figure 8 illustrates Lobban's model. The stress trajectories of Lobban's model represent the propagation of stress through the soil. The mutually perpendicular curves show the trajectories of the major and minor principal stresses. Tangents to the curves at any point represent the directions of the principal stresses at the point[28]. Lobban concluded that (a) varying the shear strength of the soil changed the size of the overstress zone (Figure 8) very little for given boundary conditions, but lowering the cohesion of the soil substantially increased the span and height of the overstress zone, and (b) if the collapsed debris that accumulated at the springings of an arch were removed, the boundary conditions changed and a new, larger arch configuration would form. Iterative analysis showed that repeated removal of the collapse debris resulted finally in a stable arch configuration that differed for different cohesion values. The stable arch configuration might be a surface-connected trajectory, or sinkhole such as the dashed curve of Figure 8.

Lobban's conclusion that a stable arch can be rendered unstable by removal of the accumulated debris at its springings infers that sinkholes probably will not form in arched soils unless sufficient percolating water is

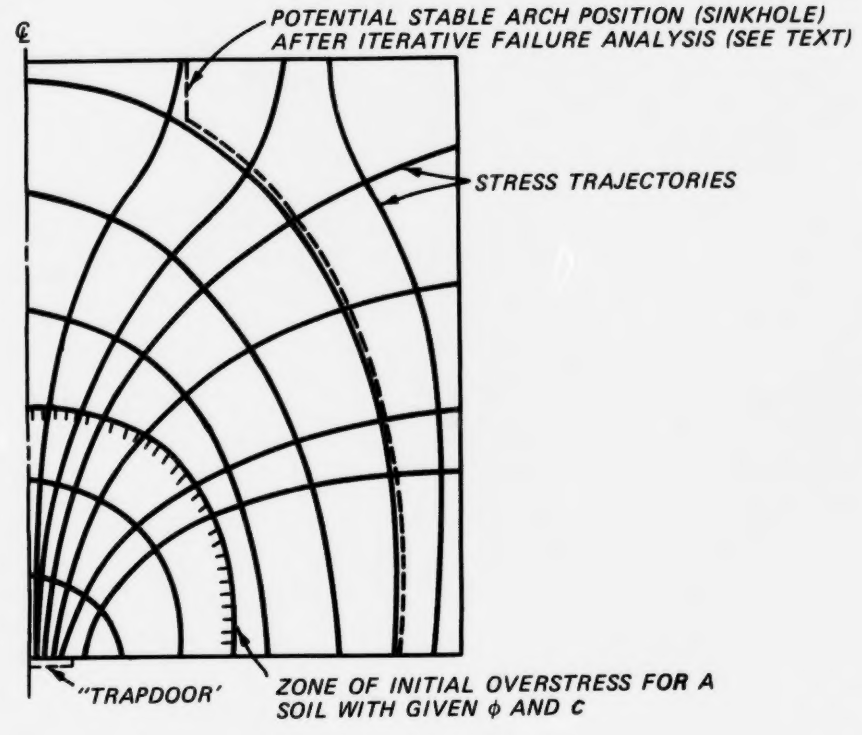

℄
POTENTIAL STABLE ARCH POSITION (SINKHOLE) AFTER ITERATIVE FAILURE ANALYSIS (SEE TEXT)
STRESS TRAJECTORIES
"TRAPDOOR"
ZONE OF INITIAL OVERSTRESS FOR A SOIL WITH GIVEN φ AND C

Figure 8. Representation of Lobban's "trapdoor" mathematical model for analyzing arch failure propogation in soil (after reference 8).

introduced to transport debris away from the arch and to lower the cohesion in the soils. It can further be inferred that arching that develops in soils overlying cavities in waste fills will not progressively enlarge if the movement of liquids within the fill is controlled and additional water is prohibited from entering the fill.

LANDFILL SUBSIDENCE

Sanitary Landfills

Subsidence mechanisms in sanitary landfills have been documented or proposed by several investigators[9,29,30,31]. Mechanisms identified were:

- a. Primary consolidation and secondary compression (mechanical).
- b. Ravelling or piping of fill soils or debris into voids or cavities.
- c. Deterioration and subsequent collapse of voids or cavities in waste products by corrosion, oxidation, combustion (physico-chemical) or decay (biochemical).

Sanitary landfills commonly contain large amounts of paper and other organic materials that decay and significant amounts (5-10 percent reported by Sowers[9]) of rubber products that are compressible but elastic. Leachate control systems and liners generally are not employed in sanitary landfills nor is waste placement generally given special attention. On the other hand, hazardous waste landfills do not typically contain large amounts of biodegradable materials. Therefore, subsidence mechanisms identified for sanitary landfills are not wholly analogous to mechanisms expected to prevail in hazardous waste landfills.

Low-level Radioactive Waste Landfills

Daniel[20] addressed final cover performance for shallow-burial, low-level radioactive waste disposal sites and reported settlements of 6 in. to several feet. Settlement mechanisms or causes identified were:

- a. Waste consolidation.
- b. Decomposition of organic wastes (with, presumably, subsequent mechanical settlement).
- c. Collapse into cavities created by random dumping of wastes.

Settlements led to three types of identified cover (cap) problems:

- a. Cracks in the cap caused by differential settlement.
- b. Collapse of portions of the cap into cavities within the pit.
- c. Ponding of water in depressions in the cap caused by subsidence.

Kahle and Rowlands[19] investigated settlement and subsidence of trench fill for the Sheffield, Illinois, low-level radioactive waste disposal facility and identified the following causes or mechanisms of trench cover subsidence:

a. Consolidation of the backfill soils.

b. Piping or ravelling of backfill soils into cavities between waste containers or into cavities created by deterioration of wastes and waste containers.

c. Deterioration and settlement of the wastes and waste containers.

Piping and ravelling of soils at Sheffield were believed to be aggravated by infiltration of additional water into the fill through breaks in the trench cap caused by traffic, shrinkage, freeze-thaw and erosion of the cap soil cover. Consolidation of the unsaturated backfill was presumed to occur by drainage of water from the pores (primary consolidation) and by rearrangement of particles (secondary compression) under the fill's own weight. Deterioration of waste containers like that experienced at Sheffield is expected to occur in RCRA hazardous waste facilities. The Sheffield waste settlement problems were attributed to structural collapse and corrosion of containers, particularly metal drums. Kahle and Rowlands stated that collapse of containers created cavities into which particulate materials could pipe and which could lead to development of surface potholes. However, containers should collapse only under the weight of overlying materials and therefore should not create a cavity but simply compact, with no break in continuity with the overlying and adjacent soil. The result of drum collapse more logically would be compaction (secondary compression) subsidence and not piping or ravelling into cavities. Drum corrosion might create an incipient cavity if the drum contained free liquids or trapped gas (air) but corrosion of the drum would probably lead to its collapse and to closing of any incipient cavity. It is conceivable that bridging or arching of soils overlying cavities created by drum corrosion (but not by drum collapse) might occur if more corrosion resistant materials or containers surround the corroding containers to serve as rigid abutments to bear the arching forces of overlying soils.

Subsidence Mechanisms in Controlled Hazardous Waste Landfills. Most of the controlled (RCRA) hazardous waste landfills addressed in the study are recent (post - 1977) and have not as yet exhibited subsidence problems. Waste and waste placement characteristics, fill and fill placement characteristics, and other operational procedures were studied for several controlled facilities to predict the probable settlement/subsidence mechanisms that might be active in the fills. The dominant mechanism is expected to be deformation or compression of waste products, fill soils, and voids. Water contents of the wastes may be high but the landfill will not be saturated (for reasons discussed in Section 5 of this report). Saturation will continue to decrease as leachate is removed via the leachate collection system. Some of the water of the waste and fill becomes chemically bound as water of hydration and is not readily available as leachate. For these reasons subsidence by consolidation will occur much more quickly than in the case of saturated landfill soils. Calculations explained in Section 4 indicate that consolidation of intermediate cover layers will occur in a short time, prior to final closure of the landfill.

Some cavities are present in the cells at closure but the careful placement of waste containers and intermediate cover practiced in the typical controlled facility will keep cavity size small. Cavities created later by deterioration or corrosion of wastes or waste containers will also be small because containers are not allowed to contain more than 5 percent void (cavity) space (10 percent under 1982 interim guideline revision, USEPA[3]) and may not contain free liquids. As discussed earlier, container collapse should result in compaction but not cavity enlargement or sinkhole development. The stringent leachate collection and liner systems of the controlled facility preclude the development of escape paths, pipes, or excessive gradients that might trigger cavity collapse or growth.

A layer of corroded or deteriorated waste containers can be analyzed as a deformable layer in a fill with variable layer compressibilities. A layered fill model can be constructed using properties of typical waste-intermediate cover materials and typical landfill geometries. Deformation and settlement can then be calculated for fills of varying stiffnesses and the relationship between subsidence and fill properties developed. The method used in this report to analyze and model the deformation by settlement of typical hazardous waste landfills is described in Sections 4 and 5.

SUBSIDENCE-RELATED COVER PROBLEMS

Documented examples of failure (compromise) of landfill final cover systems resulting from final cover subsidence and fill settlement are primarily for low-level radioactive waste repositories and sanitary landfills. Four types of final cover compromise that have been identified are:

a. Differential settlement of fill and final cover leading to the development of tension cracks in the final cover, diagrammed in Figure 9A for low-level radioactive waste[20], and for landfills[5]).

b. Settlement of fill and final cover leading to ponding of water on the final cover, as shown in Figure 9B[5,20].

c. Local sudden collapse of final cover soils into underlying cavities in the fill, as shown in Figure 9C[20].

d. Piping of erodible final cover soils into underlying cavities in the fill, leading to collapse, or sinkholes, as in type c above for low-level radioactive wastes[19]).

Another type of documented final cover problem not caused by settlement, but which can lead to the development of piping failures is cracking of the final cover by desiccation or by freezing and thawing of water in the final cover soils (Kahle and Rowlands[19]). Cracking, if deep enough, allows water to infiltrate and, if the water is of sufficient volume and if cavities or other seepage paths are present within the fill, can initiate piping of erodible final cover soils with eventual final cover collapse.

The kinds of final cover problems considered in this study (prior to modeling) to be most likely to occur in controlled (RCRA) hazardous waste landfills were tension cracking by differential settlement and ponding of surface water in subsidence depressions. As discussed earlier, piping and sinkhole development are not expected to be significant because the volume of cavities and avenues of piping within the fill will be minimized by careful waste placement. Leachate collection systems and solidification of liquids will help maintain unsaturated conditions. Active hazardous waste disposal facilities examined during this study have not yet experienced significant cell final cover difficulties attributable to settlement. Apparently insufficient time has elapsed since closure of the first cells of RCRA-controlled facilities for settlement and subsidence effects to be noticeable. More significantly, it may be difficult to document other than sudden cover subsidence because the disposal facility operators will correct slow or minor cover subsidences as they occur by the use of grading equipment and fill soils.

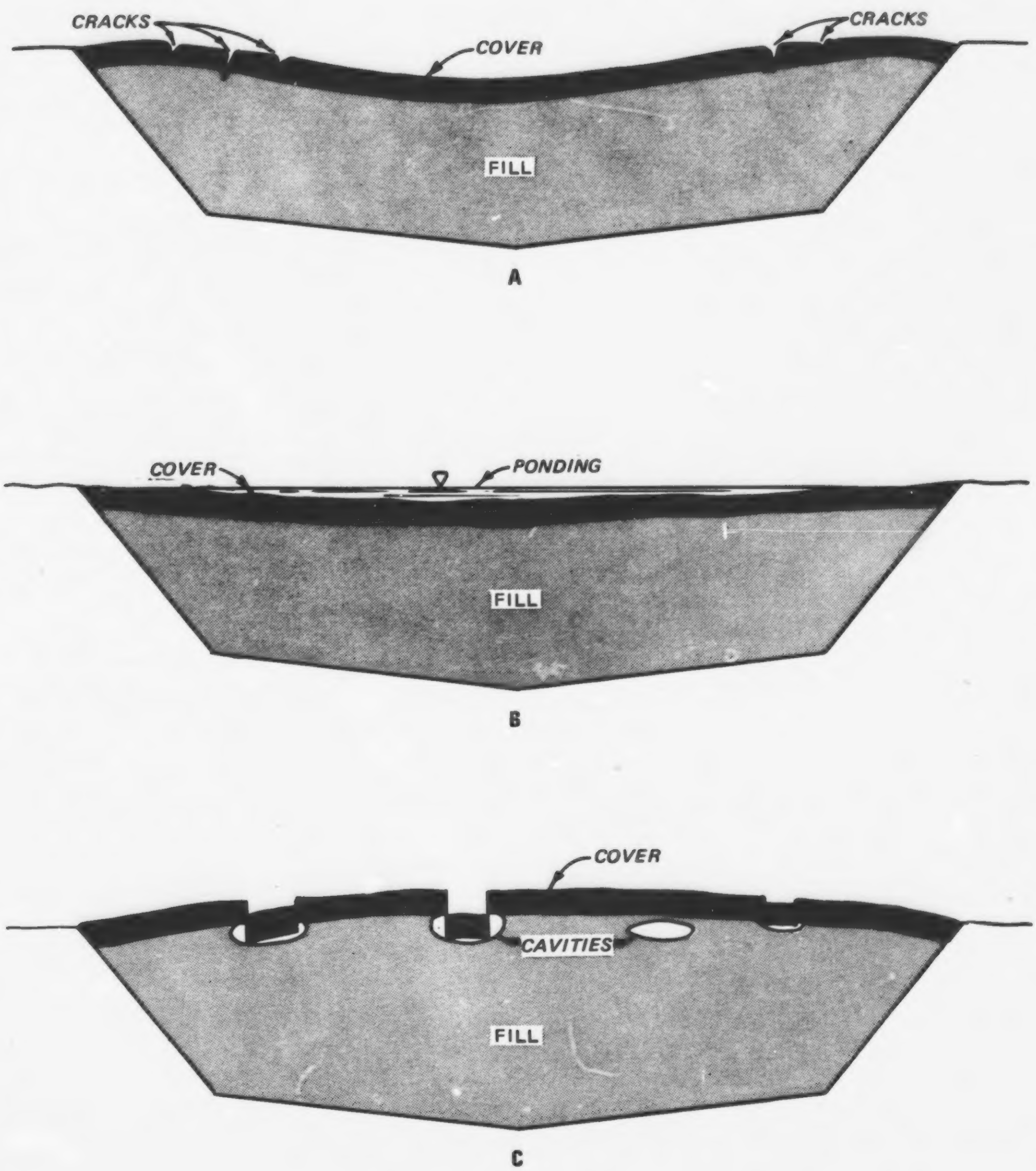

CRACKS
CRACKS
COVER
FILL
A
COVER
PONDING
FILL
B
COVER
CAVITIES
FILL
C

Figure 9. Cover problems identified and documented for landfills.

SECTION 4

PREDICTION MODELS FOR MAXIMUM SUBSIDENCE

INTRODUCTION

This section presents numerical methods of analyzing the deformation in a typical hazardous waste landfill to predict the amount of settlement of the fill and subsidence of the final cover. It may be several years before comparison can be made between the numerical method results and actual field final cover performance. The models selected to represent the typical hazardous waste landfill in the numerical analysis techniques are representative of actual landfills encountered during this study. Waste and intermediate cover characteristics (such as densities, water content, fill and waste layer moduli and compressibility), leachate barrier characteristics (such as permeability, thickness, and elastic moduli), compaction procedures and specifications, and other considerations represent real materials and operational procedures found in the hazardous waste landfill industry. The models developed and the results of analysis presented in this report are thought to be valid within the limitations discussed and under assumptions made in Sections 4 and 5.

One design consideration for hazardous waste landfills is a liner system to serve as a barrier between waste and in situ soil which intercepts leachate that either has been internally generated by the contained waste or is the result of infiltration of liquid from the outside during filling. Liner systems often consist of layers of clay compacted in place to a predetermined water content and density to achieve a required permeability. The liner system may consist of clay alone or clay in combination with one or more polymeric membranes. The effect of long-term exposure to chemical waste environment on the liner is unknown but for the purpose of this analysis it will be assumed that the liner system remains intact for the life of the structure.

After closure, landfills must have a final cover to prevent human (and animal) contact with the waste, to prevent wind dispersion of the waste and to prevent liquids from percolating into the landfill so that the production of contaminated leachate is minimized. In this light, it is important that the final cover system remain intact and competent because rupture of the final cover could cause a landfill to fill up with water and overflow, spreading contaminated waste and toxic chemicals into the environment.

PURPOSE OF MODEL ANALYSIS

Simply stated, a hazardous waste landfill is a large excavated pit where wastes are buried, sandwiched between layers of intermediate cover soil. The intermediate cover soil and the layers of waste are subject to compression from the weight of the overlying material. Surface subsidence by internal material compression and settlement can be a problem if it is so severe that it causes the final cover to crack or to impound rainwater which might eventually seep into and breach the final cover. Subsidence must be considered if long-term protection is to be provided for these structures. To avoid subsidence of the center of the cover and the resulting water impoundment, such structures might be overbuilt by the amount of expected subsidence so that the ground contour would reach the design grade as ultimate subsidence occurred. Accordingly, an estimate of subsidence must be made. The purpose of this chapter is to establish soil and stress conditions in a typical hazardous waste landfill and to estimate surface subsidence for various landfill configurations. Two analyses were made in this study: (1) to determine maximum subsidence to be expected before and after closure at the center of a large landfill for two waste placement configurations, and (b) to determine the potential for cracking of the cover by stresses from differential settlement across a uniformly layered landfill.

CONDITIONS ASSUMED FOR LANDFILL SUBSIDENCE MODELING

Geometric Configuration of Modeled Landfill

The geometric configuration of a landfill is governed by several factors including the amount of land available, size and type of equipment available to work the landfill, state and local policy concerning such facilities, projected utilization, local climatic conditions, thickness and geologic character of the native soil and rock at the site, in situ soil strength and proximity to the water table. After considering several geometric configurations (see section 1), a representative configuration was chosen and is shown in half-section on Figure 10. The excavated section is 50 ft below the original ground surface, the pit is 200 ft wide at the bottom, and the side slopes are 1 vertical on 3 horizontal for a total excavated width of 500 ft. The final cover system has approximately 5 percent (1 vertical on 20

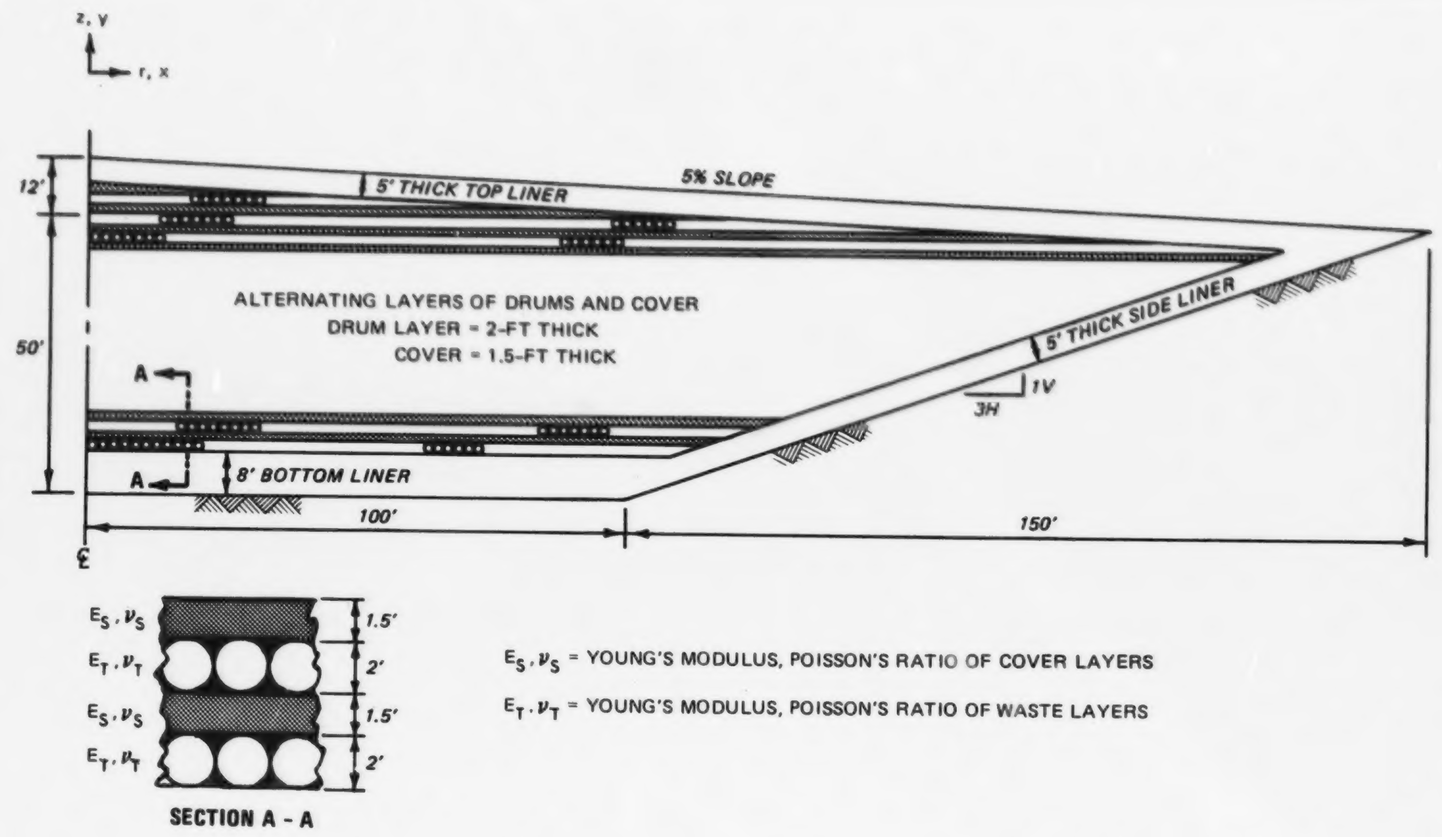

z, y
r, x
12'
50'
5' THICK TOP LINER
5% SLOPE
ALTERNATING LAYERS OF DRUMS AND COVER
DRUM LAYER = 2-FT THICK
COVER = 1.5-FT THICK
5' THICK SIDE LINER
1V
3H
A
A
8' BOTTOM LINER
100'
150'
℄
E_S, ν_S
E_T, ν_T
E_S, ν_S
E_T, ν_T
1.5'
2'
1.5'
2'
SECTION A - A
E_S, ν_S = YOUNG'S MODULUS, POISSON'S RATIO OF COVER LAYERS
E_T, ν_T = YOUNG'S MODULUS, POISSON'S RATIO OF WASTE LAYERS

Figure 10. Assumed hazardous waste landfill configuration.

horizontal) slope from the original ground surface up to the crown of the landfill for a total center depth of 62 ft. The plan of the landfill may vary from square to a rectangle whose length is many times the width of the section.

Landfill Contents

The landfill is assumed to be lined with a clay layer 8 ft thick along the bottom and 5 ft thick along the sides and top. The waste material is assumed to be contained in 55 gallon steel drums which, inside the landfill, can be laid on their sides or placed on end. The interior of the cell is assumed to be filled with alternating layers of drums separated by 1-1/2-ft-thick intermediate soil cover layers up to the top liner. The total waste-intermediate cover fill thickness is approximately 49 ft at the center. For the purposes of this analysis, the layers are assumed homogeneous and isotropic which means that layers containing the metal drum will be a homogeneous "equivalent" of metal drum, contained waste and that portion of the intermediate cover soil that is placed in the spaces around the drums. The drums are nominally 2 ft in diameter and 3 ft long which means that the waste layer will be 2 ft thick in the configuration where the drums are placed on their sides; waste layers will be 3 ft thick in the configuration where drums are placed on end. As implied in Figure 10, the cell is symmetric with respect to a vertical axis through the center of the landfill. With this geometry and the assumption of homogeneous material properties, it can be shown that settlement due to gravity stress will be maximum along the vertical centerline of the structure because of maximum cell depth at the centerline and maximum distance from the interference of the boundaries.

Landfill Soil Conditions and Water Content

Because of regulation and practical consideration, liner systems of hazardous waste landfill facilities are designed to satisfy a permeability rather than a strength requirement. The maximum value of permeability permitted by the EPA is 1×10^{-7} cm/sec. Laboratory permeability is typically measured on remolded soil specimens which have been back pressure saturated in triaxial chambers. The liner and intermediate cover materials used within the landfill are almost always of the soil excavated initially from the landfill site. For several observed sites, the excavated soil is a medium plasticity clay whose Atterberg limits are shown in Table 1.

Table 1

Atterberg Limits of Typical Hazardous Waste Intermediate Cover Materials and Model Material

Site Location	Liquid Limit (%)	Plasticity Index
Alabama	32-48 (38 avg)	12-30 (18 avg)
South Carolina	65-75 (68 avg)	20-30 (24 avg)
New York	46-54 (50 avg)	26-33 (30 avg)
Model material (Vicksburg buckshot clay)	56	34

The clay chosen for use in the model is "Vicksburg buckshot" clay, a plastic (Unified Soil Classification CH) clay whose stress-strain and strength properties are well documented[32,33]. The clay's liquid limit is 56 percent and its plasticity index is 34 percent. This clay exhibits a stress-strain behavior typical of remolded compacted clay over a wide range of confining pressure. A typical stress-strain response is shown on Figure 11. The landfill site is assumed to be completely above the water table. Therefore, for the purpose of this analysis, the degree of soil saturation is assumed to be less than 100 percent. For the mathematical model, the liner system is considered to be well compacted clay. It is assumed to have a dry density of 113 pcf and a water content (weight of water per weight of solids) of 19 percent for a moist unit weight of 135 pcf. The intermediate cover soil is considered to be less compacted than the liner soil. Frequently the intermediate cover soil is spread over a waste layer by a piece of earth moving equipment and compacted by driving the equipment back and forth over the soil. Lutton et al.[5] determined by systematic correlation between laboratory compactive effort and passes of an intermediate sized bulldozer on landfill intermediate cover layers that 3 to 4 passes correspond to a dry density of about 92-93 pcf dry density in a silt or clay soil with an in situ water content of about 25 percent. This matches closely with the water content and density conditions of the compacted laboratory soil specimen of clay that was selected as the model soil[33]. For the intermediate cover material, a dry density of 92 pcf, a specific gravity of 2.8 and a water content of 25 percent corresponds

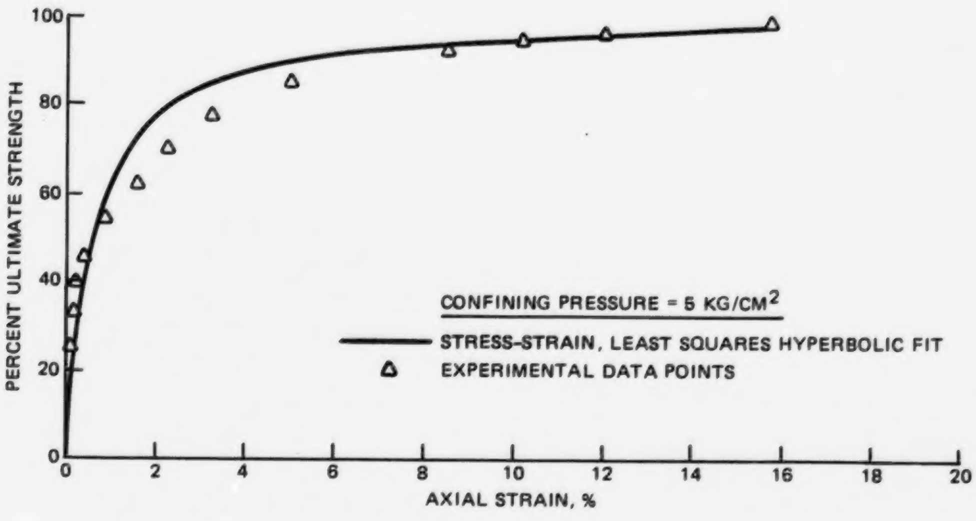


Figure 11. Stress-strain relationship for CH soil chosen for liner and intermediate cover. Reference 33.

to a saturation of about 78 percent and a wet unit weight of 115 pcf, which is believed to be a realistic and expected in situ soil condition. The wet weight of the waste layers is also estimated to be 115 pcf for modeling purposes. Index properties of the modeled soils are summarized in Table 2.

Table 2

Index Properties of Modeled Liner and Intermediate Cover Soils

	Compactive Effort	Dry Unit Weight (pcf)	Wet Unit Weight (pcf)	Water Content (%)	Saturation (%)	G_s
Liner clay	High	113	135	19	97	2.8
Intermediate cover clay	Low	92	115	25	78	2.8

Boundary Conditions of the Landfill Section

For the purpose of this analysis, it will be assumed that the geometric section of the landfill has rigid boundaries, that is, significant deformation takes place only within the material inside the landfill section with no movement of the boundaries. This assumption is justified in that the excavated clay is at least normally consolidated and probably quite stiff and strong at a depth of 50 ft below ground level. Due to unloading as a result of excavation, some rebound may occur but exprerience has shown that rebound is small relative to virgin compression (compression for the first time) of soil. Since the weight of soil removed from the section is probably more than the weight of the waste material redeposited, normal stress at the boundaries is decreased, therefore, no significant additional compression should occur along the boundaries. Any recompression that does occur will only tend to return the boundaries to their original position. These rebound and recompressive excursions at the undisturbed boundaries will be so small relative to deformation occurring inside the landfill that they will be neglected.

In addition, it will be assumed that upon excavation of the cell to final grade, the undisturbed ground surface will be covered with either a polymeric membrane or a layer of remolded clay that will protect the undisturbed soil surface and ensure that the soil will neither swell from the possible absorption of rainwater, nor desiccate due to water loss from evaporation.

Two settlement/subsidence conditions are considered. The first makes use of the finite element method (FEM) and looks at settlement during the construction and filling of a hazardous waste landfill cell. The second uses mathematical integration to develop an equation to predict subsidence due to changes in material properties after cell closure. Both treatments are necessary for completeness. The consideration of settlement during construction may offer a method of obtaining in situ material properties based on measurements made during construction. The second and most important treatment (postclosure subsidence) is necessary because layers consisting of wastes in steel containers (drums) will deteriorate with time and subsidence will occur as a result.

MODELING OF PRECLOSURE MAXIMUM SETTLEMENT/SUBSIDENCE

Finite Element Settlement Analysis

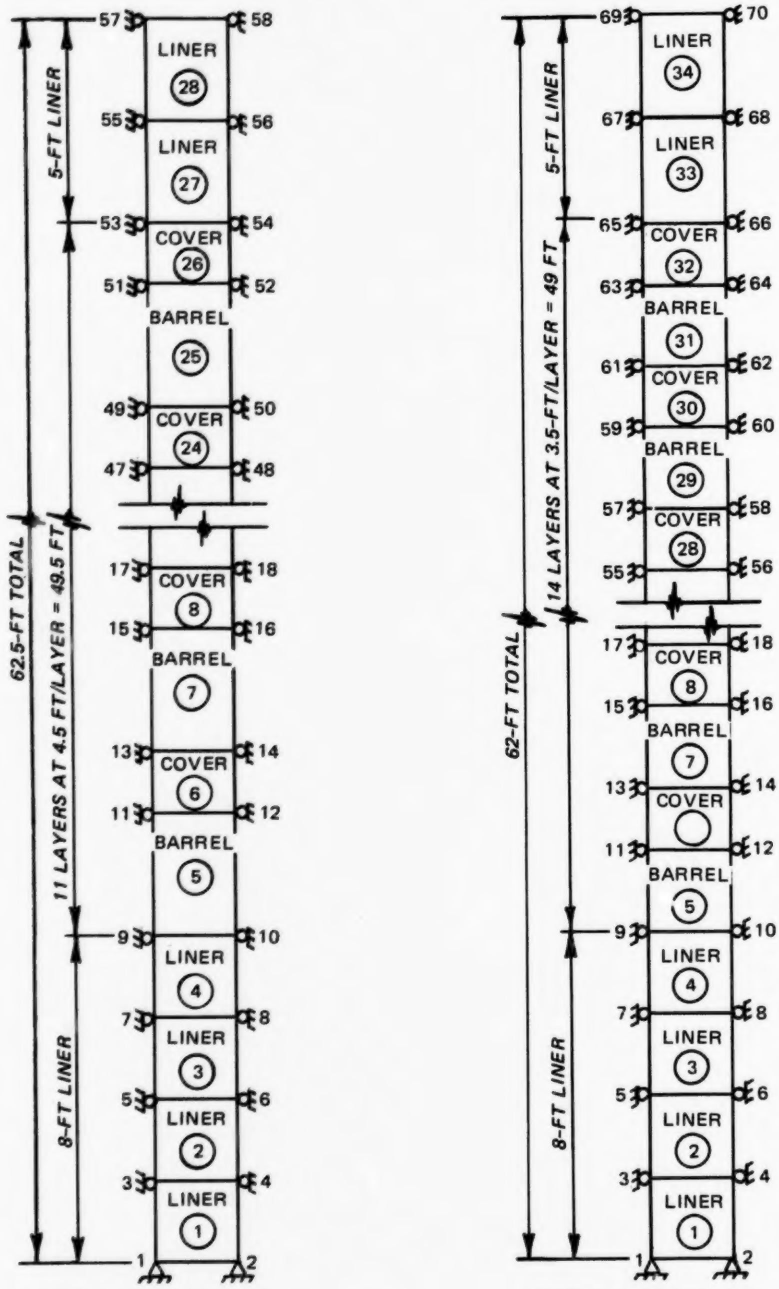
A finite element computer code is used to compute settlement during filling in the geometry selected as a typical landfill cell. The code employed uses a five node isoparametric quadrilateral[34]. Within this element, strain is assumed to vary linearly while constant strain is imposed along the element boundaries to satisfy interelement compatibility.

The code itself (named AXIPLN) was written by J. L. Withiam and F. H. Kulhawy[35] and features the use of two nonlinear materials with hyperbolic stress-strain characteristics and one linearly elastic material and the capability to build and/or excavate elements. The hyperbolic stress-strain soil characteristics used in this study were taken from actual laboratory test data on the CH soil (Vicksburg buckshot clay) described above. The hyperbolic relationship used in the computer code was determined by a least squares fit of the laboratory data in the manner described in Withiam and Kulhawy[35]. The actual data points as well as the fitted curve used in the analysis are shown on Figure 11.

The code also features the "slip" element which allows transverse displacement between layers of elements to release a selected limiting shear force. Even though this capability was not utilized in the present analysis it could be very useful in cases where soil is placed against a polymeric membrane where a low coefficient of friction between unlike materials could cause slip. Another important feature of the code is that it allows the material modulus to increase as confinement due to gravity stress or self weight increases[36]. This makes the analysis much more realistic since the loading scheme in this modeling was that of building up the total structure by stacking one layer on top of the other and allowing vertical stress and all around confinement to increase in a systematic experimentally verified manner as the layers are placed. The code and its use are described in detail in Withiam and Kulhawy[35].

The minimum intermediate cover layer thickness within the cell is assumed to be 1-1/2-ft thick which is a reasonable and practical field-observed value. However, intermediate cover layers as thin as 6 in. and as thick as 4 ft have been observed. Because of operations involved in numerical evaluation by the computer code, it is necessary to maintain the aspect ratio of the finite elements within the structure at approximately one, which means that square elements are preferred and the most skewed quadrilateral element permitted is one with an aspect ratio of 3.[37] Numerical integration is required in the finite element procedure and numerical errors become more significant as elements become longer and more slender. Errors are also introduced because elements with widely dispersed aspect ratios have different stiffnesses which do not match properly in the same structure and which may not satisfy compatibility requirements. In a structure as large as the one under consideration as shown on Figure 10, it would be necessary to design a grid containing 900-1000 elements to model layers 1-1/2-ft thick in order to avoid large numbers of elements with inappropriate aspect ratios. Such a grid would prove difficult to manage and prohibitively expensive to run on the computer.

However, an inspection of the landfill geometry and some reasonable simplifying assumptions will allow a considerably smaller problem to be considered. The central portion of the landfill is 200 ft wide and typically more than 200 ft long. Maximum subsidence will, because of symmetry, occur at the geometric center of the landfill. Maximum subsidence is the condition sought because if it is known, the grade of the final cover can be designed on the basis of the maximum expected subsidence and therefore the crown will settle, in time, to the acceptable level. Therefore, a column of appropriately layered soil, 2 ft wide, supported by vertical rollers at the edge and pinned on the bottom will be analyzed (see Figure 12). The column is a practical, useful and reasonable model because:



62.5-FT TOTAL
5-FT LINER
11 LAYERS AT 4.5 FT/LAYER = 49.5 FT
8-FT LINER
57
58
LINER
28
55
56
LINER
27
53
54
COVER
26
51
52
BARREL
25
49
50
COVER
24
47
48
17
18
COVER
8
15
16
BARREL
7
13
14
COVER
6
11
12
BARREL
5
9
10
LINER
4
7
8
LINER
3
5
6
LINER
2
3
4
LINER
1
1
2
62-FT TOTAL
5-FT LINER
14 LAYERS AT 3.5-FT/LAYER = 49 FT
8-FT LINER
69
70
LINER
34
67
68
LINER
33
65
66
COVER
32
63
64
BARREL
31
61
62
COVER
30
59
60
BARREL
29
57
58
COVER
28
55
56
17
18
COVER
8
15
16
BARREL
7
13
14
COVER
11
12
BARREL
5
9
10
LINER
4
7
8
LINER
3
5
6
LINER
2
3
4
LINER
1
1
2

a. FINITE ELEMENT GRID FOR BARRELS ON END

b. FINITE ELEMENT GRID FOR BARRELS ON EDGE

NOTE: CIRCLED NUMBERS ARE ELEMENT NUMBERS.
UNCIRCLED NUMBERS ARE NODAL POINT NUMBERS.

Figure 12. Finite element grids chosen for landfill subsidence model.

a. The one-dimensional subsidence of the column will simulate the most severe subsidence in the landfill.

b. A reasonable number of elements may be used to model the structure.

c. More realistic loading at practical cost can be applied to the structure.

d. Element aspect ratios may be used which minimize numerical error and which allow better representation of thin layers.

e. Plain strain loading in both horizontal directions is applied in the computer analysis. This type of stress system is appropriate because the column analyzed is 1 ft in "radius" and the vertical edge of the column of elements is from 100 to 150 ft away from the landfill boundaries (see Figure 10). The structure of interest is from 100 to 150 "radii" from the boundaries and it can be argued that due to the rapidity of stress decay with distance from a loaded boundary[36,38,39], the influence of a boundary is generally not significant beyond 10 radii and can be neglected. Therefore, central column deformation will be one dimensional and support of this column on vertical rollers is justified.

Observation has shown, in fact, that actual landfills are typically so large in areal extent that accurate estimates of maximum subsidence presumably may be made by central column analyses even in instances where symmetry is not present. The reason is that the central column is too far from the boundaries for the stresses and strains in the center of the cell to be influenced.

As was mentioned above, two fill geometries will be considered in which the waste layers are 2 and 3 ft thick, representing cases where drums are laid on their sides and placed on end, respectively. The two FEM grids are shown on Figure 12a and 12b. The center column representing the structure is 2 ft wide and because the intermediate cover layers are 1-1/2-ft thick, each layer will be represented by one element. The aspect ratios will be 1.33, 1.00, and 1.50 for elements representing intermediate cover layers, drums on their sides, and drums on end, respectively.

Simulation of Preclosure Loading and Settlement

The approach to simulation of preclosure landfill settlement was to apply the landfill layers one at a time and allow the underlying material to be compressed by the weight of all above it. This approach closely simulates field loading since prototype cells are filled gradually by the placement of waste layers which are then covered with soil. The finite element code computes the displacements and stresses due to self weight loading based on the strength properties assigned each layer. Because the deformation involved in this study is along the center line of a symmetric body, movement will be one dimensional and no shear deformation will occur. This means that the column of particles along the center line will move downward without rotating and consequently no shear stress will develop. Confining pressure or mean normal stress increases with increased burial depth but the computer model compensates by increasing the modulus of the nonlinear soils according to an exponential formula derived and described in Withiam and Kulhawy[35].

A linear elastic parametric study varying E and ν of the waste layers was performed. For each computer run the Young's modulus and Poisson's ratio of the waste layers were varied. The intermediate cover layers are assumed nonlinear and deform according to the hyperbolic constitutive relationship described above. Poisson's ratio is assumed constant for the intermediate cover layers. The effects of Poisson's ratio are discussed below, but for the present it may be stated that the value is not expected to change enough during loading to influence the results appreciably.

Deformation will begin to occur in the prototype cell immediately after the placement of material. The magnitude of the deformation will depend on the stiffness of the waste and intermediate cover layers. In the model study, properties of the waste layers are varied for each computer run to determine the amount of settlement that will occur for those particular values and Figures 13 and 14 were developed using this approach. It must be realized that any subsidence of the final cover that occurs as a result of settlement of the fill during construction and filling of a hazardous waste landfill will be compensated at the time of closure by bringing the crown of the cover to the proper elevation. For example, if 20 in. of settlement/subsidence were to occur in the typical cell during filling, the crown would not be left 20 in. low; it would be brought to the design elevation. Consequently, during the building of the cell, 20 extra inches of material would have been added to the cell. Figures 13 and 14 suggest that if the waste drum layers are very stiff, that is if they have a sufficiently high elastic modulus which does not decrease during construction, the subsidence that has occurred upon capping of the cell amounts to about 13 and 10 in. for the drums-on-their sides and drums-on-end conditions, respectively.

Settlement/subsidence that occurs during construction is of secondary interest because it is compensated before closure. However, the filling of a

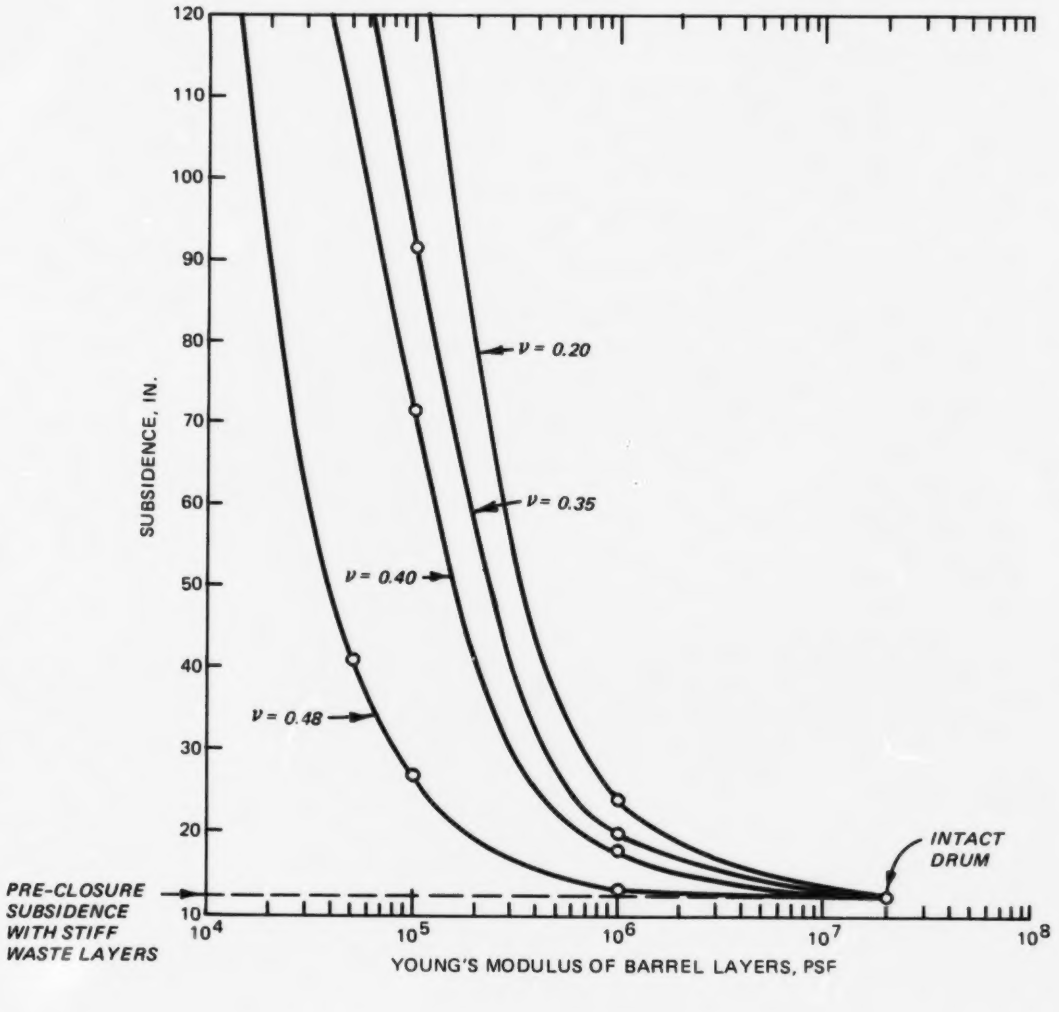


Figure 13. Preclosure subsidence prediction curves for drums-on-side configuration.

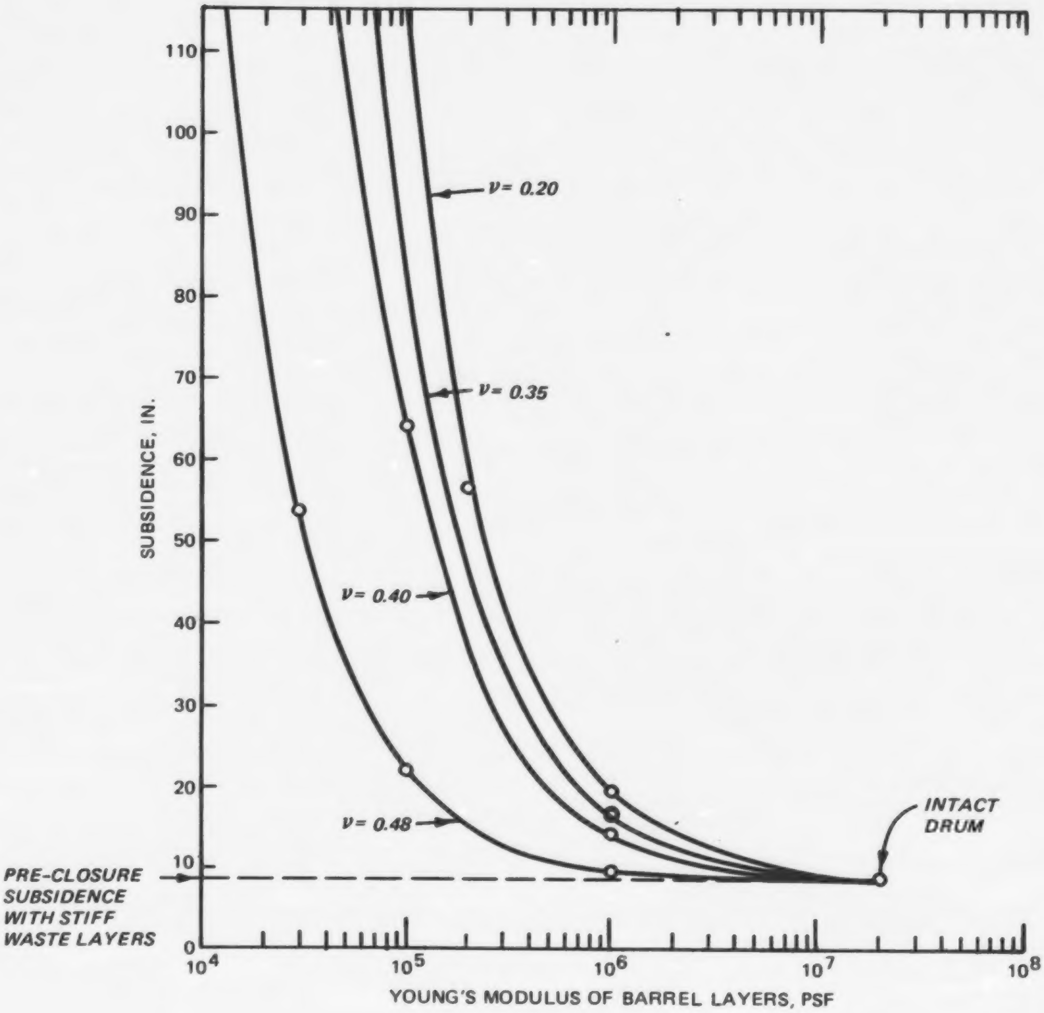


Figure 14. Preclosure subsidence prediction curves for drums-on-end configuration.

cell represents a field loading situation and, if a cell is properly instrumented during construction, in situ material properties, the rate of container deterioration and the consequent time decay of waste layer stiffnesses may be determined. This information would be of great value in evaluating the potential for later settlement and subsidence.

Figures 13 and 14 are based on incremental loading and show subsidence with respect to Young's modulus and Poisson's ratio. Properties of waste and cover materials may be back-calculated from field measurements made during construction. However, these measurements must be used with relationships based on incremental loading such as Figures 13 and 14 because the load-deformation relationship based on "sudden loading" or "gravity release" loading (discussed below) is different from that of incremental loading. The relationships are best illustrated by Figure 15, which contains information taken from all the incremental load computer printouts. The vertical axis of the figure is the average vertical stress at the centerline of the cell as the layers are placed. The horizontal axis is the subsidence expressed as a percent of the maximum subsidence which will occur. The average vertical stress when the structure is 62.5 ft deep (filled and capped) is about 3700 psf. The zone of scatter around the average line is caused by the superposition of different values of Poisson's ratio on the plot. Different Poisson's ratios give rise to different confining pressures, moduli, and subsidence. The nonlinear nature of deformation with average vertical stress is apparent from Figure 15.

In the "sudden-loading" case, which is considered next and which addresses the solution for postclosure material properties changes, deformation is linearly related to vertical stress. Therefore, if meaningful properties are to be derived from measurements obtained from instrumented representative landfills, the proper loading history must be considered.

Behavior of Intermediate Cover Layers

Due to symmetry and maximum distance from the boundary, maximum subsidence will take place at the geometric center of the cell. Because of the relatively thin (18-in. thick) unsaturated layers of intermediate cover soil and the long period required to fill a cell (projected to be from 1 to 75 years) primary consolidation of the intermediate cover layers can be shown

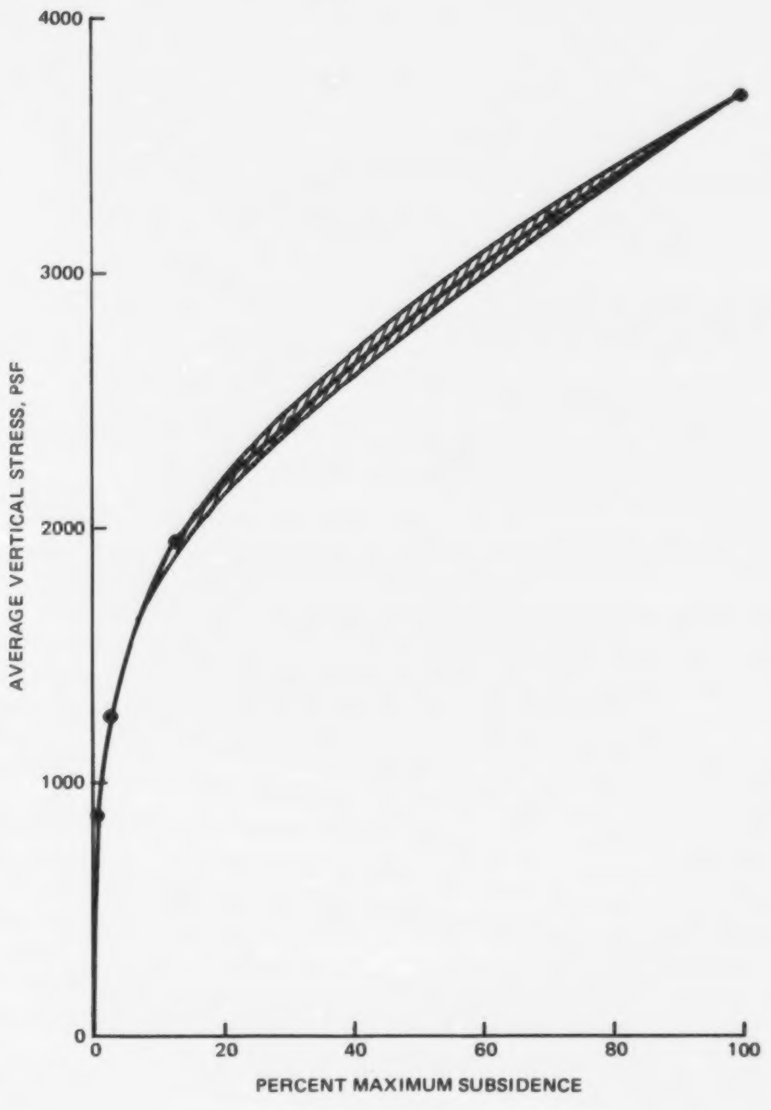


Figure 15. Average vertical stress vs percent maximum subsidence.

to be essentially complete by the time the filled cell is capped. For example by using Equation 6 if the time for 90 percent consolidation is desired, Hc = 9 in. = 23 cm, $T_{90} = 0.85$, and c_v is 1.5×10^{-4} cm^2/sec, then t_{90} can be computed to be about 34 days, which is a comparatively short time in the period of filling a hazardous waste cell. Coefficient of consolidation, c_v, has been correlated with liquid limit by Terzaghi and Peck[26], and the upper limit of these data is enveloped as is shown on Figure 16. The equation for the envelope has been determined. Recalling Equation 6, if the soil intermediate cover layer thickness is 2Hc cm and the liquid limit of the soil in percent water content is LL, then the time in days required for 90 percent consolidation of the cover layers can be expressed as

$$t_{90} = H_c^2 \times 10^{(.0168LL - 2.2)} \tag{7}$$

(derived from Equation 6 and Figure 16 after conversion of units) based on the conservative envelope of Figure 16. Using this equation and a liquid limit of 60 percent (which corresponds to a c_v of 1.5×10^{-4} in Figure 16), t_{90} may be computed to be 34 days.

MODELING OF POSTCLOSURE SUBSIDENCE OF THE LANDFILL AS A RESULT OF MODULUS DECREASE

Factors Contributing to Total Subsidence

Since primary consolidation in the intermediate cover layers can be shown to be essentially complete at closure in the hazardous waste landfill under consideration, then except for relatively small amounts of secondary compression, postclosure subsidence will be the result of closing of cavities and the degeneration and softening of the waste drum layers. The stress condition in the cell at the end of filling is determined and it may be reasonable to assume that it does not change after capping (closure). Therefore, any further subsidence in the landfill will be the result of changes in the elastic properties of the waste drum layers. The cover layers have already been shown to contribute very little to subsidence, so for the treatment which follows, cover layers will be ignored with only the waste layers considered to contribute to subsidence. In equation form, total subsidence, S_T, may be represented as

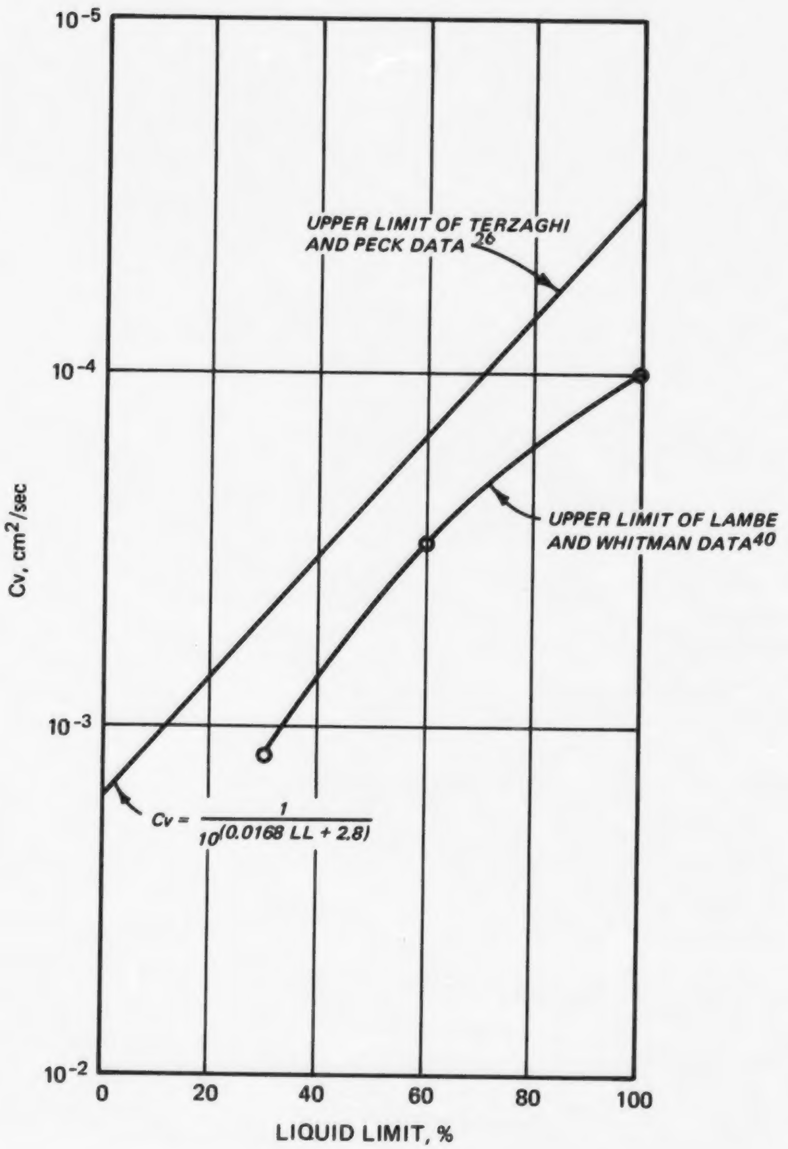


Figure 16. Coefficient of consolidation vs liquid limit.

$$S_T = S_{ISL} + S_{LV} + S_{DV} + S\ _{E} \tag{8}$$

where

S_{ISL} = subsidence due to consolidation of the intermediate cover layers

S_{LV} = subsidence due to closing of the inherent geometric layer void space

S_{DV} = subsidence attributed to void space inside the drums. This component is assumed to be zero, but should be quantified and accounted for in a general approach

$S_{\Delta E}$ = subsidence due to change in stiffness of the waste layers

The maximum volume of void, or cavity, that can be included in the landfill by drum placement may be calculated geometrically for drums placed on their sides and for drums placed on end. The maximum cavity volume for the former is 10.73 percent of the total landfill volume and for the latter is 9.31 percent. If the cavities close completely, the maximum total subsidence must be the sum of cavity closure plus subsidence by compression of the landfill contents. However, actual landfill operations will reduce maximum cavity volume because the operations do not achieve perfect drum placement and because filling of interdrum space by sifting of cover soils during filling generally occurs to some extent. Conversely, any unexpected void within the drums would contribute to the volume of inherent cavity.

Deformation by Degradation of Waste Layer Modulus

For the sake of simplicity and so that time does not enter the analysis, the treatment given here will be that of linear elasticity. The end product of this treatment will be the amount of subsidence or the potential for subsidence caused by a decreasing waste-layer modulus, given in terms of the pertinent parameters, but the work will not address how the subsidence occurs with time.

Assume again a central column (Figure 17) of length L and consisting only of waste material. The cover layers have been removed. The distance from the top of the layer to a differential element dy is y. The edges of the column ride on rollers so that the area of the column does not change. Plane strain conditions exist in the column. Therefore

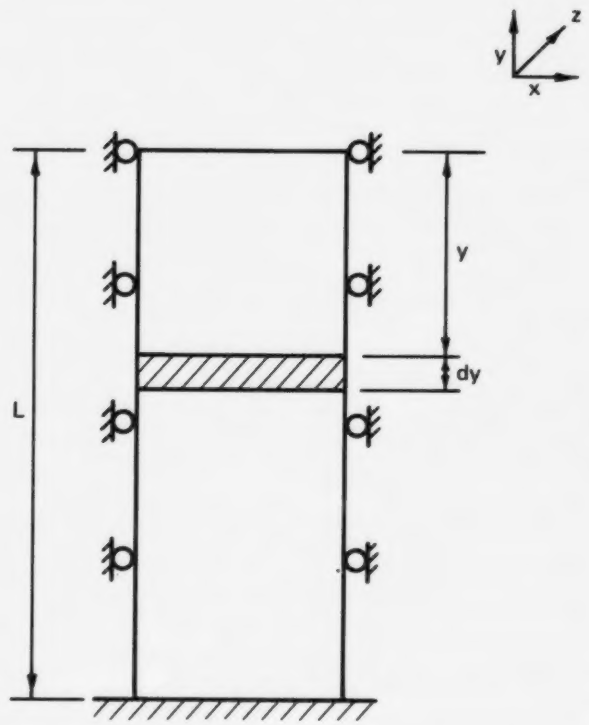


Figure 17. Schematic of central column and coordinate system for subsidence model.

$$\varepsilon_y = \frac{1 + \nu}{E} (\sigma_y (1 - \nu) - \nu\sigma_x) \tag{9}$$

$$\varepsilon_x = \frac{1 + \nu}{E} (\sigma_x (1 - \nu) - \nu\sigma_y) \tag{10}$$

$$\varepsilon_z = 0 \tag{11}$$

where ε_x , ε_y , ε_z = strain in the x , y , and z directions, respectively.

σ_x , σ_y = stress in the x , y directions, respectively

E = Young's Modulus

ν = Poisson's Ratio

The lateral stress σ_x is the product of the coefficient of earth pressure at rest, K_o , and the vertical stress, or

$$\sigma_x = K_o \sigma_y \tag{12}$$

which can be shown to be

$$\sigma_x = \frac{\nu}{1 - \nu} \sigma_y \tag{13}$$

Combining Equations 9 and 13 yields

$$\varepsilon_y = \sigma_y \frac{1 + \nu}{1 - \nu} \quad \frac{1 - 2\nu}{E} \tag{14}$$

Combining Equations 10 and 13 yields

$$\varepsilon_x = 0 \tag{15}$$

The vertical stress

$$\sigma_y = \gamma y \tag{16}$$

where

γ = the unit weight (density) of the medium.

By definition, strain, ε , is the ratio of the change in length to the total length of the body or

$$\varepsilon = \frac{\Delta L}{L} \tag{17}$$

Therefore the strain in the differential element, dy , of Figure 17 is the change in length divided by the original length which, expressed in differential form, becomes

$$\varepsilon_y = \frac{d\ (dy)}{dy} \tag{18}$$

Combining Equations 14, 16, and 18,

$$\frac{d\ (dy)}{dy} = \gamma\ y \left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{E}\right) \tag{19}$$

Therefore,

$$d\ (dy) = \gamma \left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{E}\right)\ y\ dy \tag{20}$$

Integration of Equation 20 results in the summation of the deformation in all differential elements over the length L of the column. Therefore,

$$\int_o^L d\ (dy) = \Delta L \tag{21}$$

where

ΔL = the total change in length of the column.

Combining Equations 20 and 21

$$\Delta L = \int_o^L \gamma \left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{E}\right) y\ dy \tag{22}$$

and

$$\Delta L = \frac{\gamma\ L^2}{2} \left(\frac{1+\nu}{1-\nu}\right)\left(\frac{1-2\nu}{E}\right) \tag{23}$$

Note that Equation 23 contains no stresses and suggests that the subsidence that is at the cell center and therefore maximum, varies directly with the density of the waste fill and with the square of the waste depth and inversely as the stiffness, E . This means that a column of material with density γ , length L and elastic properties E and ν will deform an amount ΔL if suddenly "released to gravity" from a completely weightless state. Now from this point, if the elastic modulus E begins to decrease and deteriorates from an initial value E_i to a final value E_f then the resulting subsidence will be

$$S_{max} = \frac{\gamma L^2}{2} \left(\frac{1 + \nu}{1 - \nu}\right) (1 - 2\nu) \left(\frac{E_i - E_f}{E_i E_f}\right) \qquad (24)$$

and if the change in elastic modulus is known, S_{max} may be computed directly from Equation 24. $S_{max} = \Delta L_f - \Delta L_i$ and Equation 24 is derived by direct substitution of ΔL_f and ΔL_i into Equation 23.

Effect of Poisson's Ratio

Poisson's ratio (ν) logically changes and influences the results as subsidence occurs, but the manner in which it changes is not clearly understood. Lambe and Whitman[40] suggest that the value of ν can usually be estimated with satisfactory accuracy as 0.35 for soils of low saturation and 0.5 for fully saturated soils. The value of 0.5 will enforce material incompressibility and consequently no subsidence will occur at that Poisson's ratio. At the opposite extreme, a Poisson's ratio of zero indicates behavior where a vertical stress causes vertical strain but no tendency for horizontal strain. A material such as loose snow has a Poisson's ratio approaching zero. Practically, waste in a hazardous waste landfill will be neither of these extremes but something in between. Lambe and Whitman[40] recognized the difficulty of making an exact evaluation of Poisson's ratio for use in any problem, but suggested that the value usually has a relatively small effect on engineering predictions. Craig[41] states that during consolidation Poisson's ratio decreases from the undrained value to the drained value at the end of consolidation. The decrease does not affect the vertical stress and slightly decreases the horizontal stress, but this decrease is neglected in the Skempton-Bjerrum method of consolidation settlement prediction.

Al-Hussaini[42] performed K_o tests on sand under conditions of triaxial compression. During the K_o tests, radial strain was not permitted and the horizontal and vertical stresses were measured and vertical strain occurred. The ratio of horizontal to vertical stress under these conditions is, by definition, K_o. These tests showed that K_o remained constant during loading up to axial pressures of 300 psi. Since K_o and Poisson's ratio are related in linear elasticity by the equation

$$\nu = \frac{K_o}{1 + K_o} \qquad (25)$$

if K_o remains constant during deformation then so does ν , Poisson's ratio. Al-Hussaini shows that for the material being tested the value of K_o varies from about 0.6 at a relative density of 20 percent to a value of about 0.4 at a relative density of 100 percent. Equation 25 would suggest a corresponding variation in Poisson's ratio of about 0.38 down to 0.29 for the same range of relative densities. Donaghe and Townsend[43] performed K_o tests on a very plastic clay (liquid limit = 79, plastic limit = 26) and showed a change in K_o from 0.52 to 0.64 over an interval of axial stress from 7 psi to 85 psi. This is a change in Poisson's ratio from 0.34 to 0.39.

The conclusions of the above investigators suggest either that Poisson's ratio does not appear to vary significantly during deformation or that a change in Poisson's ratio does not affect the results significantly. For these and also the reason that no analytical plan has yet been formulated to vary Poisson's ratio during loading, it will be assumed that the value remains constant. Settlement and subsidence, then, will occur primarily as a result of a decrease in the Young's Modulus, E , of the waste layers.

Use of the Subsidence Equation

This paragraph explains how the subsidence equations and accompanying curves are used to compute the expected subsidence caused by degradation of wastes in a landfill. Equation 23 has been graphically represented on Figures 18 and 19 for the typical cell under consideration with on-side and on-end drum disposal, respectively. For the on-side drum disposal configuration, the typical fill has 14 drum layers at a thickness of 2 ft for each layer for a total compressible thickness of 28 ft. Similarly, the total waste layer thickness for the on-end drum disposal configuration is 33 ft. Therefore, the values for L in Equation 23 are 28 and 33 ft, respectively. The value for waste material density is taken to be 115 pcf in the typical cell. The value of the material elastic constant, Young's modulus, is varied and the subsidence curves are shown for four values of Poisson's ratio. As an example, assume that in a waste cell 62.5 ft deep at the center, there are 28 ft of drum-waste layers (on-side configuration) with an average density of 115 pcf. Say that the initial Young's modulus and Poisson's ratio were determined to be 5×10^5 psf and 0.35, respectively. This establishes one point on Figure 18 (drums on their sides). Now say it is determined from laboratory tests or

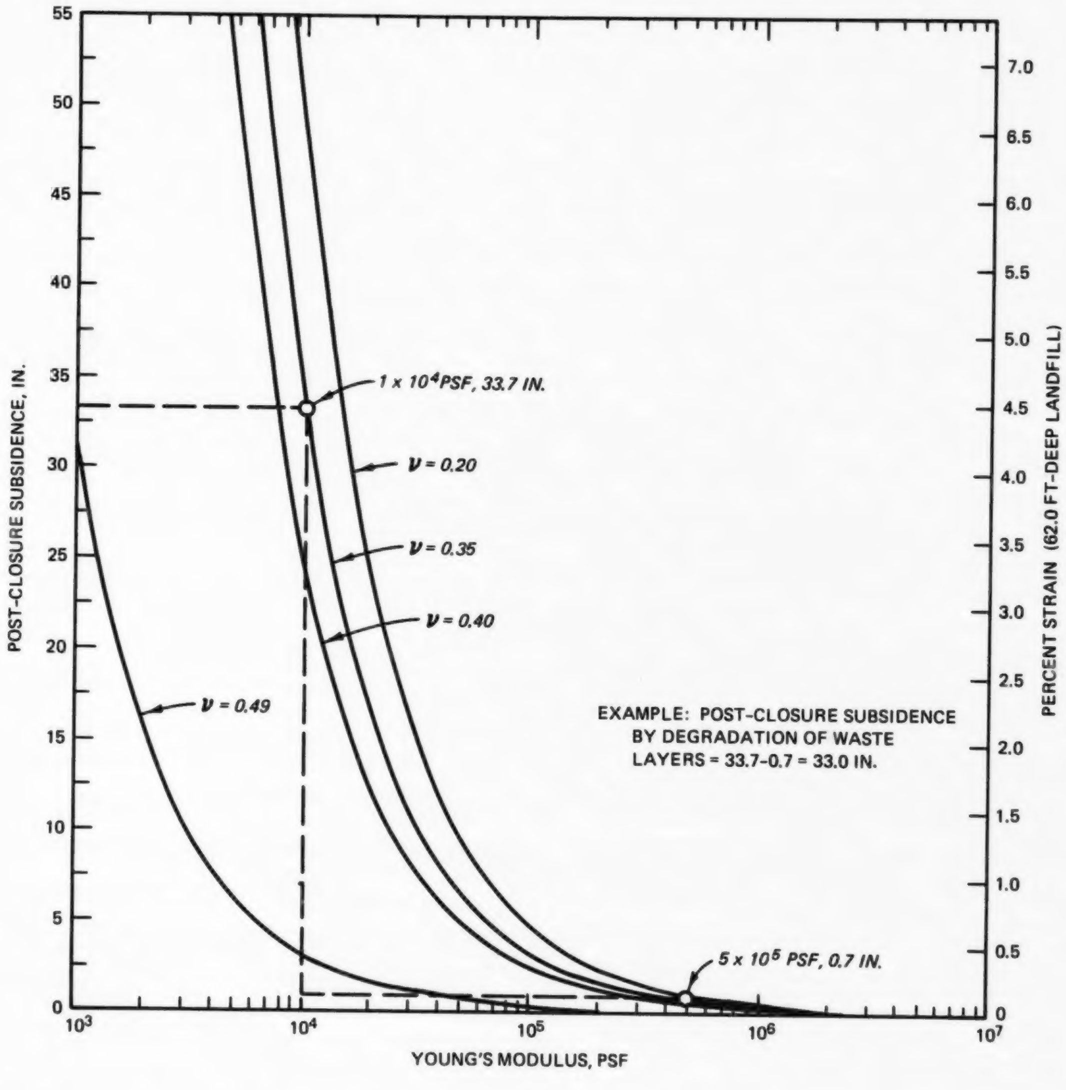


Figure 18. Post-closure subsidence prediction curves for drums placed on their sides.

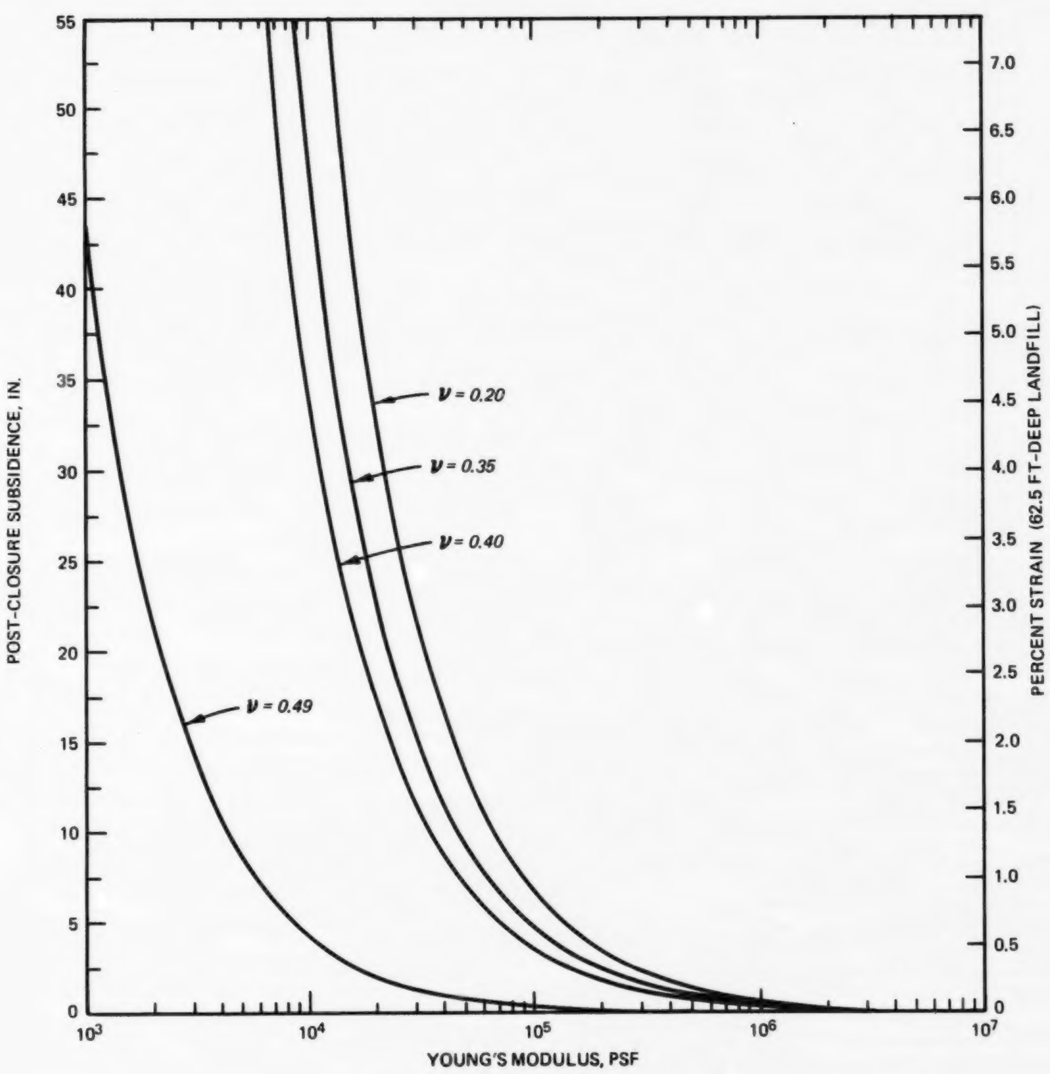


Figure 19. Post-closure subsidence prediction curves for drums placed on end.

extrapolated from field experience and measurement that the Young's modulus of the waste drum layers could decrease to 1×10^4 psf with the value of Poisson's ratio unchanged. This establishes the second point on the figure and therefore the subsidence that would occur as a result of this change in modulus at constant Poisson's ratio ($\nu = .35$) is the change in ordinate from the first to the second point which is

$$33.7 - 0.7 \text{ inches} = 33 \text{ inches (see Figure 18)}$$

The same value would be obtained by using Equation 24 and substituting in the values $\gamma = 115$ pcf, $L = 28$ ft, $\nu = 0.35$, $E_i = 5 \times 10^5$ psf and $E_f = 1 \times 10^4$ psf. Additional subsidence prediction curves can be generated with Equation 23 for other landfill geometries by applying different values of L (total waste-layer thickness), γ (waste layer density) and, if justified, ν. Equation 23, Figures 18 and 19, and Equation 24 can be applied to hazardous waste landfills of any depth, with either on-end or on-side layered waste placement configuration, and for any waste/container stress-strain moduli and densities. The above example demonstrates the general use of the subsidence curves and equations. The following paragraphs evaluate the maximum subsidence expected to occur for worst case conditions in landfills composed of representative materials.

Estimate of Maximum Expected Subsidence for Representative Moduli

Drums on Their Sides. Steel drums buried on their sides may be ideally represented by an elastic cylinder subjected to the application of external pressure only. The drum has a typical wall thickness of 0.050 in., an inside diameter of 22.25 in., a Young's modulus of 30×10^6 psi and a Poisson's ratio of 0.29. From the basic assumption, typical dimensions and material properties, the equations of an elastic hollow cylinder[44] were rearranged to show that the effective elastic modulus E_D of such a cylinder subjected to an isotropic change in external pressure is

$$E_D = 9.7 \times 10^6 \text{ psf*}, \text{ where } E_D = \text{modulus of the drum} \qquad (26)$$

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* See derivation in Appendix B.

The repeating geometric unit representing the idealized drum buried on its side is shown on Figure 20. The space shown shaded above the drum is assumed to be filled with soil. The space below the drum is taken to be an air cavity so that maximum subsidence may be estimated. The intermediate cover layers have been shown above to be undeforming in the terminal condition (closure of the landfill) so they have been removed. Therefore for the purpose of analysis the cell can be considered to consist of stacks of the basic building blocks of Figure 20.

The soil in the system is taken to be the same clay described above for use as intermediate cover. Consolidation tests performed on this material at the indicated density[45] within the stress levels of interest show that the constrained secant modulus of this soil is approximately 104,000 psf.

If it is assumed now that the clay present above the drum is subjected to the same uniform pressure as the drum and that the total volume change in the system is the sum of the volume change of the drum and the volume change of the soil, then it can be shown that the elastic modulus of the composite system with intact drums is related by

$$E_{Ti} = \frac{4\,E_D\,E_s}{\pi\,E_s + 4E_D\left(1/2 - \frac{\pi}{8}\right)} \qquad (27)$$

where E_{Ti} = Initial elastic modulus of the composite system, in psf

E_s = Elastic modulus of intermediate clay cover material, in psf

E_D = Elastic modulus of the waste drum, in psf

If now the moduli of 104,000 psf (E_s) and 9.7×10^6 psf (E_D) are substituted into Equation 27, then a value of 900,000 psf (E_{Ti}) is obtained for the initial composite. From E_{Ti}, Equation 23 and Figure 18, it can be determined that for a Poisson's ratio of 0.35, the corresponding initial elastic subsidence in the representative landfill under consideration is approximately 0.4 in. Now assuming that the contents of the drums were initially liquids and that the contents were solidified by adding an absorbent material such as kiln-dried fuller's earth (crushed claystone), then after the steel of the drum has completely corroded away, the waste contents will be subjected to compression by existing gravity stress.

Consolidation tests were performed on two commercially available absorbent earth compounds to obtain typical constrained modulus values for these

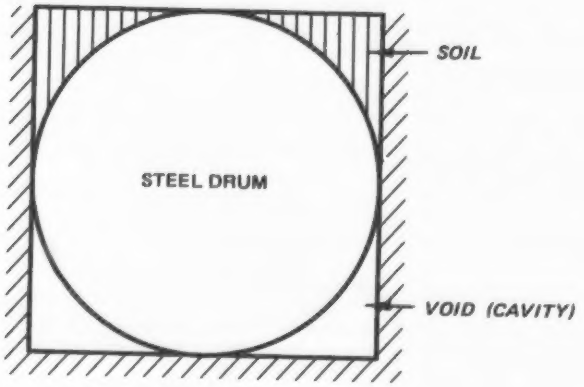
SOIL
STEEL DRUM
VOID (CAVITY)

Figure 20. Geometric configuration of drum buried on its side.

materials. Both materials were soaked in water for 48 hours to allow for the maximum possible absorption of water. The materials were then spooned into an oedometer (one-dimensional consolidation device) to simulate the probable low density achieved by the field practice of pouring the material into a drum half filled with liquid. The specimens were then loaded up to 55 psi in the oedometer in five or six increments allowing complete drainage under each increment. The results of the loading are shown on Figure 21.

The first material is sold commercially as a compound to absorb oil spills. It is basically a calcium bentonite claystone which was removed from a quarry, crushed, then kiln-dried at 1100°F (calcined). The resulting material has the appearance of a coarse angular sand with hard granules which remained hard and intact after soaking. The constrained secant modulus of this material was measured to be about 1,000 psi or 144,000 psf (see Figure 21).

The second material is sold commercially as an absorbent for use commonly as "kitty litter." The material is identical in composition to the first material except that after crushing, it is kiln-dried at only 300°F (i.e., it is noncalcined). The resulting material had the same physical appearance as the first material but after soaking became soft and plastic and the resulting modulus was measured to be about 275 psi or 40,000 psf. Since the objective was to estimate maximum subsidence, the lower modulus of 40,000 psf (the noncalcined claystone) was used in the calculations.

Referring again to Figure 20, the final configuration was analyzed in exactly the same manner as the intact drum configuration except that for the final configuration the drum volume is replaced by elastic material with a modulus of 40,000 psf (the modulus of the noncalcined claystone). If a similar analysis is performed assuming that the two materials will compress as if loaded by an isotropic pressure then the equivalent elastic modulus may be shown to be

$$E_{Tf} = \frac{4E_c\ E_s}{\pi\ E_s + 4E_c\ (1/2 - \pi/8)} \tag{28}$$

where E_{Tf} = Final elastic modulus of composite system, in psf
E_s = Elastic modulus of intermediate clay cover in psf
E_C = Elastic modulus of drum contents in psf

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* See derivation in Appendix B.

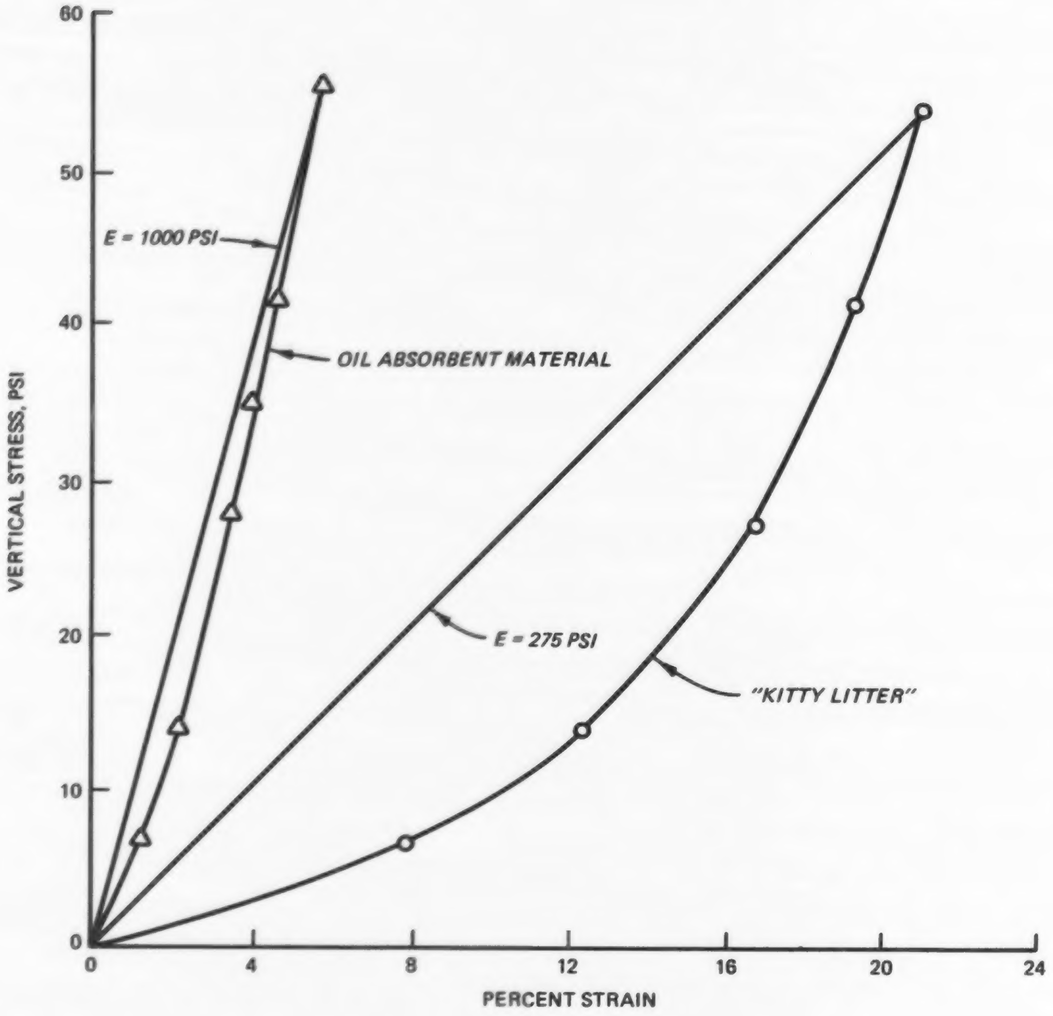

Figure 21. Constrained elastic moduli of two simulated waste materials.

If the values of 40,000 psf for modulus of drum contents and 104,000 psf for intermediate cover modulus are substituted into Equation 28, then the equivalent composite modulus is computed to be 48,000 psf. The corresponding subsidence for this value is 7 in. taken from Figure 18. Now if the initial value of 0.4 in. is subtracted, then the resulting subsidence is 6.6 in., which corresponds to 0.89 percent strain in a total height of 744 in. (62 ft). But this is not all the subsidence that can occur. The air void (cavity) beneath the drum can be shown to be 10.73 percent of the total volume. If this space closes completely during subsidence, then the total value will be the sum of the two or 10.73 + 0.89 = 11.62 percent (approximately 87 in.) for the maximum expected subsidence. If all the waste drums are assumed to contain 10 percent (allowable) void space, the additional 10 percent represents an additional 7.9 percent waste layer cavity volume (drums occupy 79 percent of the waste layer for drums on their sides). The total estimated subsidence considering 10 percent void space in the containers would then be 11.62 + 7.9 = 19.52 percent or 145 in. (12.1 ft). However, it seems unlikely that all the drums would contain the maximum 10 percent allowable void space.

Drums on End. Similarly, if drums that are buried on end are represented by hollow steel cylinders that carry the axial compressive load without buckling then the effective elastic modulus of such a structure can be shown to be

$$E_D = 3.86 \times 10^7 \text{ psf} \quad * \qquad (29)$$

which corresponds approximately to zero initial subsidence on Figure 19.

When the drum has completely corroded and the remaining material is taken to have a modulus of 40,000 psf then the final value of subsidence taken from Figure 19 is 11.7 in. This corresponds to 1.56 percent strain in a height of 750 in. It can be shown that the cavity space between drums in the densest possible stacking configuration comprises 9.31 percent of the total volume. If this space closes completely during settlement then the total value will be 1.56 + 9.31 = 10.87 percent (approximately 82 in.) for the maximum expected subsidence (drums-on-end). If all the waste drums are assumed to contain 10 percent (allowable) void space, the additional 10 percent

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* See derivation in Appendix B.

represents an additional 9.1 percent waste layer cavity volume (drums on end occupy 91 percent of the waste layer). The total estimated subsidence considering 10 percent void space in the containers would then be 10.87 + 9.1 = 19.97 percent or 150 in. (12-1/2 ft). However, it seems unlikely that all the drums would contain the maximum 10 percent allowable void space. The effects of the calculated cover subsidence are discussed in Section 6 of this report.

The analyses for the estimation of maximum subsidence were necessarily approximate but do lend analytical credence to the estimates. Material property values used in the analyses were values which either were measured specifically for this treatment (as in the case of the drum filler material) or taken from data obtained from tests on material believed to be very similar in nature and behavior to material used in waste disposal operations.

The analyses show that most (86 to 92 percent) of the subsidence that might occur will be the result of closing the cavity space associated with drum disposal. The estimate of maximum expected subsidence assumes that none of the cavity space is filled during construction and that the space closes completely during subsidence. This leads, of course, to the most liberal estimate of subsidence. Actually, two occurrences during construction will reduce the cavity space giving rise to less subsidence. First, precise arrangement of drums in a landfill is practically impossible. Material will fall into the cavity space underneath and between drums as a result of less than perfect placement. The degree of cavity filling will be dependent on material, water content, and drum placement. Obviously, there is a greater opportunity for the cavity space to be filled in upright drum disposal because of the vertical cavity spaces.

Secondly, for drum-on-side disposal, the analysis assumes radial deformation. It is more probable that the cylinder will flatten into an elliptical shape and intrude into the cavity space. This will reduce the cavity space during construction and lead to less subsidence in the terminal condition. Unaccountable factors which might lead to less subsidence are:

a. The unquantifiable filling of expected cavity space during construction of the landfill.

b. Arching or bridging over cavity space which results in the cavity remaining occluded for all time.

c. Thixotropy or the gain of strength with time at constant water content within the cover layers. This will enhance arching or bridging.

d. Reaction of soil with waste material which enhances soil strength.

Unaccountable factors which will tend to increase subsidence are:

a. Excessive and unexpected creep in the intermediate cover layers.

b. Soil reaction with waste material and biodegradation which diminishes soil strength and increases compressibility.

c. Unexpected cavity space in containers.

SECTION 5

ANALYSIS OF COVER CRACKING

SUBSIDENCE CRACKING

Cracking due to subsidence is a problem occasionally encountered in embankment dams and levees. If cracking develops, rainwater can percolate into cracks and result in some combination of erosion, reduced soil strength, and slope stability problems. If similar cracking occurs in the covers of hazardous waste landfills, rainwater will percolate into the cracks and pose the very serious threat of breaching the cover and filling the cell with water which would then have to be handled and disposed as contaminated leachate. Therefore it was considered necessary to analyze the hazardous waste structure under consideration for subsidence cracking.

Approach

The finite element grid used for analysis of subsidence cracking is shown in Figure 22, and represents the discretization of the configuration shown in Figure 10. The restriction of maintaining the elements comprising the structure to no more than a 2:1 aspect ratio was largely observed. The cover and liner thicknesses are approximately the same as that used in the central column study (Section 4) but the waste is modeled by fewer layers. Fewer layers were necessary because of the aspect ratio restriction of the elements and the rapid increase in the required number of elements as layers became thinner and more numerous. A model using many more elements would be expensive to run and would not yield better information because it is differential settlement, not total settlement, that determines the stresses in the cover.

The liner and top cover of the cell consisted of a compacted clay with the same nonlinear elastic stress-strain properties as the material assumed in the liner system of the analysis in Section 4. The waste layers were modeled as a linear elastic material so that the compressibility and volume change characteristics might be varied systematically. The moist density of the liner was assumed to be 135 pcf and that of the waste, 115 pcf. The cell was loaded and allowed to settle under gravity.

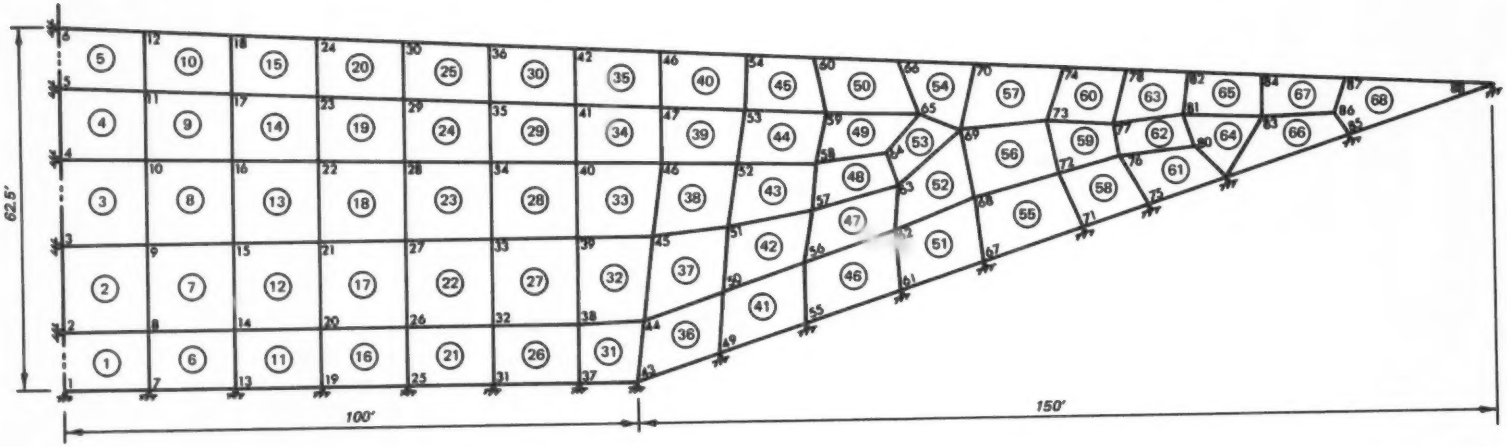

Figure 22. Finite element grid used to analyze hazardous waste landfill.

Results of Cracking Study

The evaluation of the assumed cell geometry for cracking consisted of examining the computed stress field for values of negative minor principal stress. For the geometry and soil conditions assumed, the minor principal stress field was contoured and is shown in Figure 23. The figure shows that the stress field is well behaved with no remarkable stress concentrations or singularities, and the values are all positive, indicating that there are no tensile zones. The material of the body remains in compression and there is no tendency for cracking, i.e., there is insufficient differential settlement in the modeled landfill to produce stresses that would cause the cover to crack in the manner illustrated in Figure 9A (Section 3).

The subsidence across the cell was evaluated. Several waste material compressibilities were evaluated from which it was determined that subsidence could be normalized in terms of the maximum subsidence across the cell. These results are presented in Figure 24 and show that subsidence at the center line is 100 percent of the maximum subsidence and is zero at the outermost limit (250 ft from the center line) of the cell. Vertical subsidence at any distance across the cell may then be determined by multiplying the influence factor (the % subsidence in Figure 24) by the maximum subsidence, which occurs at the center line for the desired distance. For example, a maximum subsidence value may be chosen from Figures 18 and 19 and the resulting subsidence determined all across the cell by using Figure 24.

The contour of the subsidence across the cell is shown in Figure 25, which is simply an inversion of Figure 24. Figure 25 shows that in the deepest part of the cell where the bottom is horizontal, subsidence is virtually constant, the value at the point where the bottom starts to slope upward being about 80 percent of the maximum value. This demonstrates numerically that the deepest part of the cell subsides almost uniformly and justifies the central column analysis used above in Section 4. Subsidence then decreases rapidly at an increasing rate as the edge of the cell is approached.

Factors Affecting Cracking

The results of the cracking analysis are further examined in this section. Lefebvre and Duncan[46] concluded from a finite element analysis of embankment dams that stress is a better criterion than strain for determining

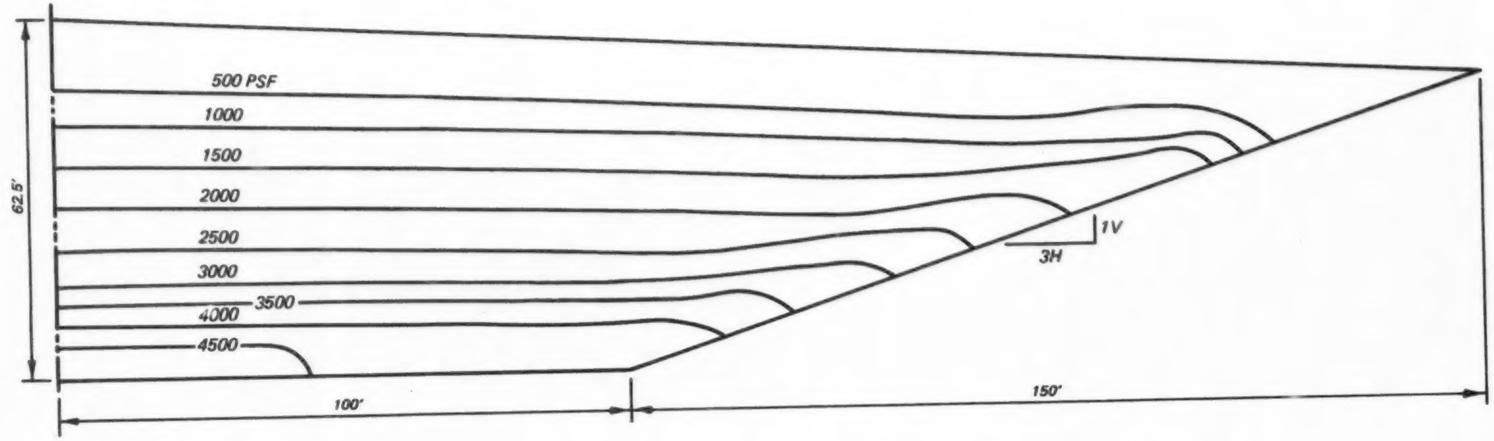
500 PSF
1000
1500
2000
2500
3000
3500
4000
4500
1V
3H
62.5'
100'
150'

Figure 23. Contours of minor principal stress in landfill.

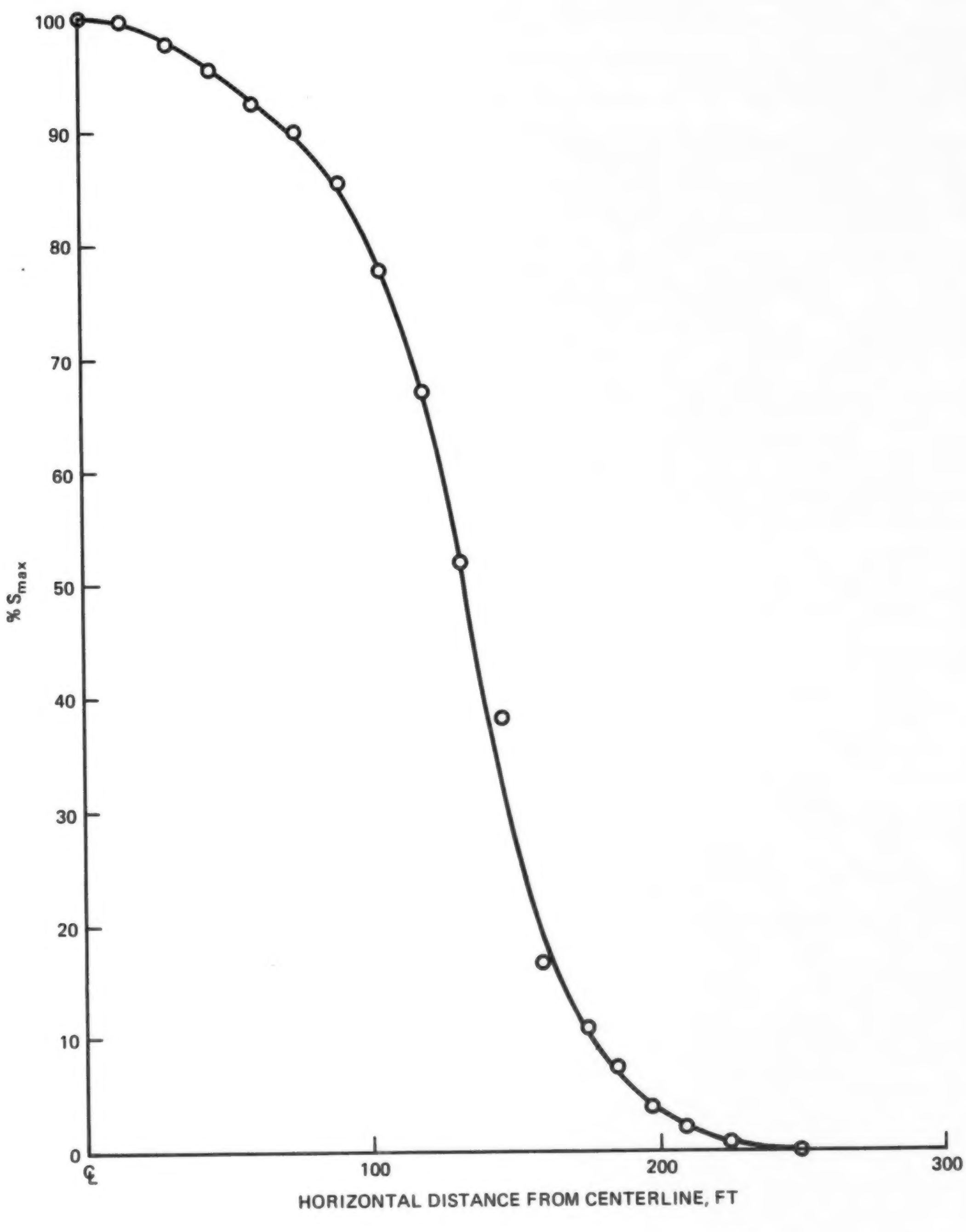

Figure 24. Percent subsidence vs distance from centerline.

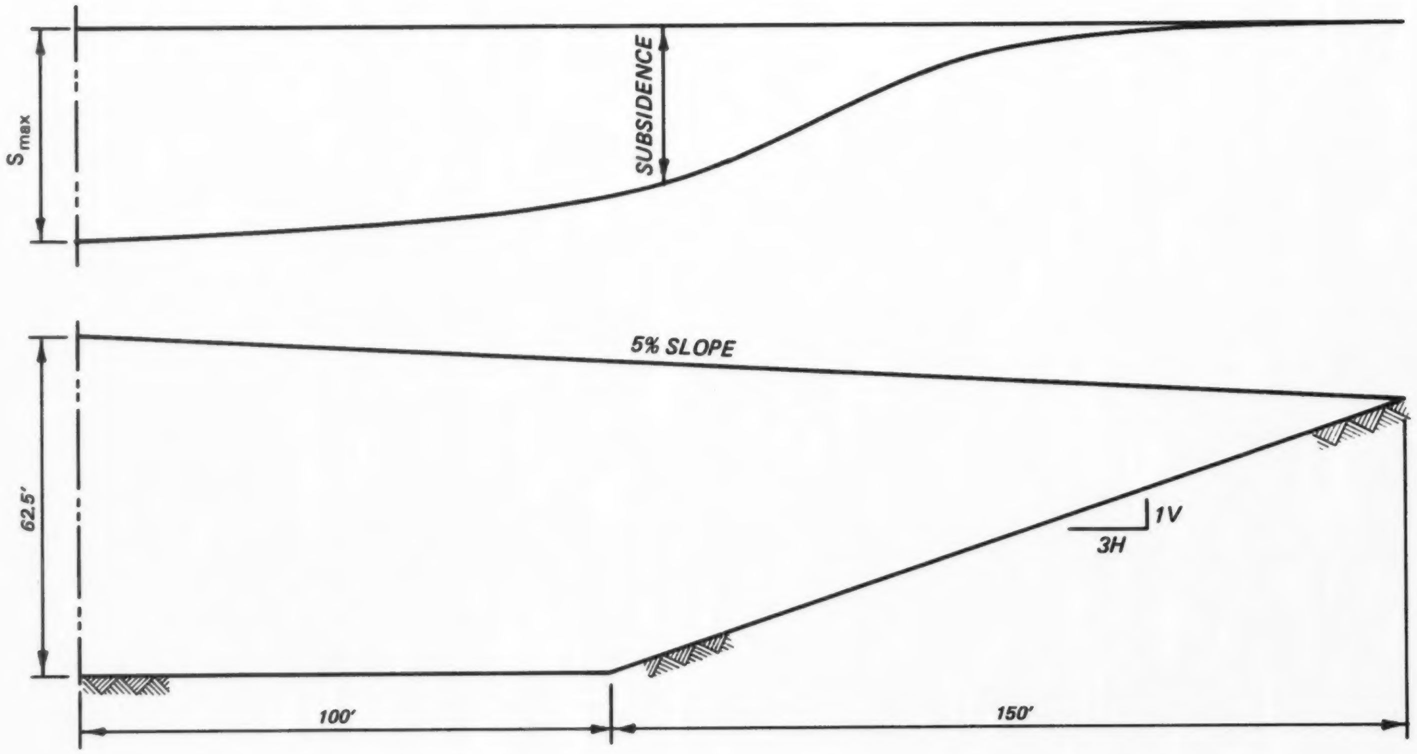
S max
SUBSIDENCE
5% SLOPE
62.5'
1V
3H
100'
150'

Figure 25. Vertical subsidence across a trapezoidal landfill.

if cracking will occur. The minimum principal stress value was the variable they examined to determine if cracking would occur. For example, if the value of the minimum principal stress became negative in a region, then the soil (which was assumed incapable of carrying tension) was presumed to have cracked in that region.

Examination of the calculated stress condition in the hazardous waste disposal cell investigated in this report revealed that tensile stresses do not develop anywhere in the structure as modeled. Landfills with nonuniform, nonhomogeneous contents were not modeled and may produce tensile stresses and resultant cracking. However, certain parallels may exist between these waste cells and the embankments examined by Lefebvre and Duncan[46]. Based on a comparison with embankments there may be several reasons why tensile stresses do not develop in the waste cells under consideration:

a. The material in the hazardous waste landfill is placed in an excavated pit which is a "bathtub-like" structure and will contain and support most of the waste material completely. It is assumed that once the cell has been filled back to the original ground level, a fairly gentle 5 percent slope will be used to build up to the crown. In an embankment dam, very often the sides slope up to the crest at 1V on 3H, for a fairly steep 33 percent slope. Thus there is probably a more severe loading condition in embankment dams than in hazardous waste landfills just due to slope steepness.

b. Lefebvre and Duncan[46] concluded that large zones of tension are more likely when an embankment dam material is very stiff. It has been observed that the fill material in hazardous waste landfills is typically not well compacted and the soil exhibits plastic rather than brittle behavior (see Figure 11). Compaction in the field is accomplished by driving a piece of construction equipment back and forth over the waste layers. This does not accomplish a high degree of compaction and, therefore, the waste layers in the cell are not very stiff. The top cover and bottom liner are typically compacted wet of the optimum water content to achieve a permeability requirement rather than a strength; therefore because of the high water content at compaction, the cover materials are more plastic and less stiff and brittle than they would be if a design strength and density had been the target of the compaction. Therefore because of the filling technique and compaction of hazardous waste landfills, the contents are more flexible and therefore less likely to develop zones of tensile stress than are embankment dams.

c. Lefebvre and Duncan[46] concluded that as the embankment becomes successively stiffer than the foundation, the size of the tensile zone and the magnitude of the tensile stresses increase. The construction of an embankment dam always involves applying more load to the foundation underneath that structure than had previously existed simply due to the additional weight of the embankment. The additional load will cause foundation deformation. In the case of hazardous waste landfills, the disposal cell will consist of a pit excavated in natural ground. The foundation material at the bottom of the cell was undisturbed ground before excavation, it had been compressed by, say, 50 ft of overburden soil for geologic time, and was at least normally consolidated. The waste material which was then placed into the cell was not well compacted and probably less dense than the excavated natural material. Therefore no additional load was applied to the foundation as a result of filling the cell with waste and it is likely that no additional deformation took place in the stiff foundation material. Therefore it was assumed in this study that the hazardous waste landfill under analysis rests on a rigid foundation. This assumption also has basis in field observation. At several sites it was observed that as hazardous waste cells were excavated, the natural material at depth became so stiff that it had to be ripped out by large and powerful bulldozers. Therefore the undisturbed foundation material is, in fact, much stiffer than the waste contents of the cell and, accordingly, any tensile zone which develops in the cell should be vanishingly small since the ratio of the modulus of the waste material to the modulus of the foundation is small.

POTENTIAL CRACKING BY DESICCATION AND SHRINKAGE

The cracking described above is strictly associated with stress and strain conditions due to body forces acting on deformable cell contents which were assumed elastic. Another mechanism which can cause cracking is shrinkage and involves the loss of water from soil by evaporation. Here too tensile stresses develop as a result of soil volume decrease and the accompanying shrinkage tensile strain. However, the difference between shrinkage cracking and subsidence cracking is that water content must decrease in order to develop shrinkage cracks, whereas cracks due to settlement are assumed to occur at constant water content.

Certain clay minerals are susceptible to shrinking and therefore cracking. Clays rich in the mineral montmorillonite are notorious for shrinkage cracking behavior. Shrinkage cracking may be controlled in desiccating environments by treating exposed soil surfaces to prevent evaporative water loss.

Sherard[47] found in a study of embankment dams that transverse cracks in dams may be caused by shrinkage when the surface of the embankment is allowed to dry out after compaction. He says that it is sometimes not possible to differentiate between shrinkage and settlement cracks and that shrinkage due to drying may accelerate and aggravate the development of cracks due to settlement and increase the widths of settlement cracks.

Surface shrinkage cracking is not the concern of this report, but it is important to realize that the potential for this type of cracking does exist and its occurrence is independent and exclusive of settlement cracking; however, the problems resulting from the two types of cracking are similar. Many investigators have studied shrinkage cracking, and Lutton, et al.[5] have summarized several practical solutions to this problem. It should be noted that shrinkage cracks due to water loss through evaporation may occur in hazardous waste landfill covers. The two types of cracks may be virtually indistinguishable and will cause similar detrimental effects. Shrinkage may pose a severe threat to cover systems in climates and seasons of high evaporative water loss, and in such climates appropriate defensive measures should be taken. Another potential problem of shrinkage or settlement cracks is the accumulation and freezing of water in open cracks. Water expands by about 9 percent upon freezing and the expansion could open cracks farther and aggravate conditions.

SECTION 6

SUMMARY AND DISCUSSION OF RESULTS

LANDFILL MODELING

Several commercially operated landfills observed during this study were large pits excavated in natural earth to depths of 50 to 100 ft. The natural earth was typically a soil or rock of low permeability. Landfill structures observed were generally lined with clay and/or synthetic polymeric membranes and equipped with a leachate collection and withdrawal system. The structures were typically filled with alternating waste layers 2 to 3 ft thick and intermediate cover layers about 1-1/2 ft thick. After filling, the landfills are capped with a permanent clay cover layer which is continuous with the sides and bottom liner system. A polymeric membrane may or may not be used in the cover. A representative model landfill section chosen for the purpose of mathematical analysis and demonstration for this investigation is 50 ft deep and 200 ft wide across the cell bottom. Sides slope up to the original ground level at 3 horizontal on 1 vertical and the cover layer slopes up to the crown at 5 percent to give a total depth of 62.0 ft at the center of the landfill. The model landfill is assumed to be constructed and filled exactly as several observed representative landfills.

Solidified material buried in steel drums is expected to make up the most significant portion of the waste in the cells under consideration. A mathematical equation based on the theory of elasticity was developed to allow calculation of maximum subsidence. Use of the equation requires input of waste properties such as density, depth of burial, and stiffness (Young's modulus). Subsidence occurs as a result of postclosure cavity collapse and waste-drum deterioration and softening. The mathematical equation predicts subsidence as a result of waste layer softening which is simulated by lowering the Young's modulus of the layers.

The equations developed in this report and their related subsidence prediction curves apply as well to horizontally layered landfills of varying depths, physical properties and geometries and are not restricted to landfills with the specific dimensions presented in this report. The analyses are for homogeneous and isotropic materials in layered, unsaturated waste cells.

Subgrade materials are presumed to be rigid (noncompressible). The site-specific amount of maximum subsidence depends on the fill depth and the physical properties of the waste, fill, cover and liner materials. Waste properties are presumed to show the most site-specific variability of all the contributing materials and are critical to the accurate prediction of subsidence. Strengths and stress-strain data of actual or simulated waste materials would permit more effective predictions of expected subsidence with the models developed for this report.

RESPONSE OF COVER TO MAXIMUM SUBSIDENCE

Analyses of the numerical settlement models developed for this study indicate that the maximum landfill cover subsidence that would be expected under worst-case conditions (deep fill, deteriorated drums and low-stiffness waste layers) would be approximately 11-1/2 percent which for the representative landfill would result in a final cover slope of about 2 percent from the crown to the landfill boundary. Most of the subsidence (around 10 percent) occurs by closing of cavities incorporated during filling. The 11-1/2 percent subsidence would not create ponding (negative slope) for the representative landfill assuming a 5 percent cover slope (12.5-ft crown) was established at closure. The resulting 2 percent slope is, however, less than the minimum suggested by EPA (3 percent) to promote drainage. Drainage off the cover is desired to prevent infiltration of standing or slow-draining precipitation with the danger of filling and overflowing the landfill (the bathtub effect) and of creating excessive leachate. An additional subsidence of 8 to 9 percent must be considered if drums are assumed to contain the maximum allowable 10 percent void space when placed in the fill. However, an assumption that all the drums would contain 10 percent void is considered realistic by the authors.

This study has shown that consolidation of the unsaturated intermediate cover (fill) layers occurs relatively soon and prior to closure. Landfills whose waste layers consist predominantly of waste-filled steel 55-gallon drums will experience additional settlement after probably several years during which time the drums and waste deteriorate to progressively lower elastic moduli and strengths. Estimations of waste layer and fill moduli for intact and deteriorated waste container conditions were made and applied to the prediction curves to derive the 11-1/2 percent maximum expected subsidence.

RESPONSE OF COVER TO SUBSIDENCE CRACKING (DIFFERENTIAL SETTLEMENT)

The analysis of the assumed hazardous waste disposal cell described shows that tensile cracking does not occur within the body of the landfill configuration modeled for this analysis. For the soil and filling techniques assumed, the stresses which would cause tensile cracking do not develop. The stress and displacement fields observed in the landfill body are well behaved and smooth with no unexpected singularities. There are several reasons for this, including the fact that the landfill material behaves plastically, yielding rather than rupturing. The foundation completely supports the waste material and is very stiff relative to the waste cell contents. An analysis of the vertical surface displacement shows that vertical movement is maximum in the center of the cell and subsidence is almost uniform over the flat-bottomed portion of the cell. This confirms that a central column analysis of subsidence is justified, and allows the subsidence at any point across a typical cell to be estimated if the center subsidence is known. Tensile stresses from differential settlement occurring in other landfills (nonuniform waste layers, for example) were not analyzed.

OTHER CONSIDERATIONS

The settlement models for this study were developed under the assumption that drained, unsaturated conditions prevailed within the landfill and that containers of free liquids were not included in the fill. It is prudent to consider the effects on settlement of including substantial volumes of free liquids, or stabilized liquids that become unstable with time, in the landfill. A liquids-filled waste drum that had deteriorated sufficiently would release its contents into the surrounding soil or soil-like intermediate cover or into bulk wastes surrounding the drum. Assuming the surrounding fill and bulk wastes were less than 100 percent saturated the freed liquids would be absorbed into the pore spaces and would increase the saturation of the fill materials. Stabilized or "solidified" liquids that might be released after deterioration of drum contents would be expected to act similarly, but with a smaller volume of liquid. The intermediate cover layers placed will be compacted with construction equipment as discussed earlier. Regardless of the compactive effort applied, two conditions of compaction are possible; compaction wet of optimum water content and compaction dry of optimum water content. If the layers are compacted wet of optimum, allowed to consolidate to 100 percent consolidation under the applied load, and then exposed to free liquid (water), volume change of the clay layer will usually be insignificant[45]. However, if the layers are compacted dry of the optimum water content, two effects might conceivably be expected as a result of post-closure release of liquid; the cover layer could tend to absorb liquid and swell (increase in volume) or collapse (decrease in volume) upon exposure to the liquid. Laboratory investigation has shown[45] that collapse of soil usually occurs at low water contents and at high stress levels, which would mean that the layers at greater depths in the landfill would tend to collapse. Volume change due to collapse is irreversible, that is, the settlement or subsidence due to this phenomenon is not recoverable. Swell usually occurs in soils at low water contents and low stress levels, which would mean for this study that layers at shallow depths in the landfill would tend to swell when exposed to water. Swell, however, may be reversible in that, as surplus water which was absorbed into the soil diffuses with time into dryer regions of the layers, shrinkage may occur and the soil may tend to return to its original volume.

Laboratory tests suggest that to minimize the problem of either swell or collapse of intermediate cover layers, compaction wet of the optimum water content is desirable. In practice, waste and intermediate cover layers of hazardous waste landfills are placed at the existing water content of the soils and no special compactive efforts are made.

At this time, no specific statement may be made regarding the effects of liquid released in a landfill. The ultimate effects of such releases would depend on site-specific factors such as the amount of liquid released, the water content of the layers at the time of compaction, the mineralogy of the intermediate cover layers, the compaction characteristics of the layers and the stress levels within the layers exposed to liquids.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Conclusions reached as a result of the study are:

a. The dominant mechanisms of settlement of the fill and subsidence of the covers of horizontally layered hazardous waste landfills are expected to be closing of the inherent drum-placement void spaces and compression of cell contents including intermediate cover soils, waste, and waste containers. Cavity related piping and sinkhole phenomena are not expected to play a major role in predicted subsidence. This conclusion is based on review of representative active waste disposal practices in industry and government and analysis of documented and theoretical subsidence mechanisms reported in other, related activities.

b. The maximum postclosure subsidence of the cover (cap) of a simulated hazardous waste landfill operating under interim RCRA guidelines, from compressibility alone, is predicted to be about 11-1/2 percent of the total height of the fill and cover at the center of the landfill. For a 62.5-ft-thick fill and cover the maximum expected subsidence, after deterioration of the waste containers, was 87 in. The final cover slope with that subsidence would be about 2 percent, which is undesirable under current RCRA guidelines. An additional 8 to 9 percent subsidence must be considered if waste drums are assumed to contain the maximum allowable 10 percent void space when placed in the fill.

c. Actual landfill settlement and cover subsidence may be less than the worst-case maximum predicted 11-1/2 percent because more of the voids between containers will probably be filled as a result of less than optimum (tight) stacking of containers during placement. The 11-1/2 percent figure is considered an effective value for design purposes.

RECOMMENDATIONS

Cover subsidence from settlement of compressible fill is expected to occur. Therefore, to minimize the severity of subsidence, managers of hazardous waste landfills should continue at least those operational methods that are being practiced at representative RCRA-guided secure landfills as determined from field observations of this study. Recommended operational methods include:

a. Landfill operators should make an effort to reduce voids when placing wastes and fill within the cell by insuring that intermediate cover soils are allowed to sift between waste containers and debris.

Drums or other containers of wastes should be filled to minimize the volume of void within the containers. Much of the potential settlement from compressibility can be eliminated by preventing the inclusion of cavities in the waste placement process in the typical hazardous waste landfill.

b. Layering of waste and intermediate cover in thin lifts so that some compactive effort is achieved during filling.

c. Control of liquids by installation of efficient leachate collection systems and stabilization of liquid wastes to prevent saturation of the fill and to allow consolidation to occur as rapidly as possible.

d. Installation and monitoring of cover settlement plates so that the subsiding surface can be maintained at the proper slope. Hazardous waste landfills should be documented, instrumented, and monitored after closure. Subsidence of the cover as well as the settlement of internal waste layers should be monitored with time in an effort to gain understanding of postclosure internal changes, how they occur, and how they affect the overall behavior of the landfill. Many of the mechanisms at work within these landfill cells can be understood only by study and experience with representative landfill cells. The data obtained by field monitoring will permit evaluation and improvement of settlement/subsidence prediction models developed in this study. Landfill operators should remember that, while the cover surface can be maintained at a proper runoff slope by the addition of soil or other material, the internal cover liner, whether a clay layer or a flexible membrane liner or both, may have been deformed and stressed by subsidence. Internal cover liner damage or deformation cannot be remedied by simple cover surface cosmetic actions.

e. Placement of a buffer thickness of intermediate cover soils above the uppermost waste layer and beneath the final cover to lessen the potential for collapse of the cover directly above locally compressible zones such as deteriorating drums.

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APPENDIX A

This Appendix presents information on design, construction, and operational characteristics for several active commercial hazardous waste landfill facilities located in several regions of the country. The 10 sites discussed were sufficiently documented during this study regarding characteristics influencing landfill settlement to allow summaries to be made of their operations. The information presented may be of use in other study areas concerning hazardous waste disposal. Table A1 summarizes the operating characteristics of the sites and describes the geometry of typical landfills (cells, pits, trenches, and cut and fill). The sites are not named but are identified by number only.

The column headings of Table A1 are clarified here. Landfill type classifies the landfills as belowground (includes pits and trenches, which may be divided into cells or subcells), combination above and belowground fills, and valley cut and fill, which is in effect a hybrid somewhere between landfill, surface impoundment, and waste pile (EPA designations). The geometry of typical or largest-sized individual landfills for a facility is described by the excavated depth (before lining and filling), the bottom dimension of the excavation, the interior side slopes, and the approximate area in plan. The actual or relative slope of the fill base is given because the slope is usually part of the leachate collection system design. The slope of the top surface of the final cover is shown where known. The column for subgrade (in-place) material describes the native soil or rock underlying the landfill and in which the landfill is placed. The specifications (specs) and descriptions of landfill liners and the final cover are given where known.

Leachate collection systems vary in their complexity, but are commonly a system of drain pipes and granular material designed to intercept and carry the leachate to a central collection point where it is removed by pumps. The forms in which wastes are buried in the landfill, for example in containers or in bulk form, are described. Many facilities segregate wastes on the basis of physical or chemical compatibility by placing them in different cells or subcells within the landfill, and the practice is indicated as shown in the table. The column for waste drum placement refers to the manner in which 55-gallon steel drums, common hazardous waste containers, are placed within

Table A1 Characteristics of Selected Hazardous Waste Landfills

Character/ Site No.	Landfill Type	Excavated Depth of Landfill	Bottom Dimensions of Excavated Landfill	Surface Area of Typical Landfill	Side Slopes	Bottom Slope (Top Surface of Liner)	Final Cover Slope	Subgrade (In-Place) Material	Depth to Water Table or Piezometric Surface	Liner Composition and Thickness	Liner Compaction Specs	Final Cover Composition	Cover Compaction Specs
1	Belowground (pits)	100 ft max.	300 x 300 ft typical	2 to 5 acres	Near vertical (80–85°)	5%, to one side	Not specified. Center is crowned.	Calcareous claystone	Not encountered	(Single) crushed, remolded claystone, 2 ft bottom, 8 ft sides	Sheepsfoot in 1 ft lifts, to 95% Standard Proctor, wet of optimum	Crushed, remolded claystone, surfaced or grassed	Same as liner
2	Belowground (pits)	40 ft max.	200 x 500 ft typical	9 acres	1V on 3H	1%, to center	5%	Siliceous claystone	(Artesian) Piezometric level at 30–40 ft	(Dual) 30 mil Hypalon synthetic over remolded clay. 5 ft bottom and sides	Sheepsfoot in 1 ft lifts, vibratory on last lift, to desired permeability, wet of optimum	(Dual) 20 mil PVC over 2 ft remolded clay. Sandy clay buffer (1 ft) between waste and liner	Same as liner
3	Combination above & belowground, diked aboveground	40 ft	—	5 to 17 acres	1 on 1 (interior)	2%, to side	8%	Clay, glacial till	--	(Triple) 2 ft clay over 80-mil high density PE, over 10 ft base	6-in. lifts to desired permeability	6-in. topsoil over 1½ ft clay over high-density PE, over 3 ft clay	Same as liner
4	Belowground (pit)	50 ft	—	3–5 acres	1V on 2.5H	Sloped to one side	No final cover planned	Clay, silty clay, silty sand	—	(Single) remolded clay-rich soil	Sheepsfoot in 6-in. lifts to 95% Standard Proctor	No final cover planned	No final cover planned
5	Belowground (trenches)	15 ft	80 x 110 ft	1 acre	1V on 1.5H	Sloped to one side	Not specified.	Clay, silty clay, silty sand	(Artesian) Piezometric level at 2–3 ft	(Single) remolded clay-rich soil 3 ft bottom and sides, or 4 ft in-place	Placed and compacted with narrow-tracked dozer	4 ft of clay-rich soil	Same as liner
6	Belowground (trenches)	12–17 ft	70 x 350 ft	1 acre	1 on 1	Sloped to center	No final cover planned	Silty clay over fine silty sand	(Artesian) Piezometric level at 2–3 ft	Unlined except where sand exposed in cut	Unlined (in place soil is barrier)	No final cover planned	No final cover planned
7	Belowground (pit)	50 ft	540 x 540 ft	Approx. 6–7 acres	Near vertical	Flat, irregular	Approx. 1% (2 ft crown in 270 ft)	Interbedded gravelly silt & clay & volcanic ash	325 ft (saline water)	Unlined: in-place soil is barrier	Unlined	Remolded clayey soil from 3 ft below grade to 2 ft crown at center	None, cover is placed with rubber-tired scrapers
8	Valley cut and fill, barrier dam at valley mouth	Planned max. depth of fill is approx. 100 ft	—	Approx. 3 acres	Cut to 1 on 1	Gentle slope down valley	Gently down valley and terraced (proposed)	Clay shale, siltstone, minor sandstone	Unknown, no usable aquifers believed present	Minimum 2 ft of remolded clay shale	Compact to desired permeability with special compactor	Final cover not yet designed	Final cover not yet designed
9	Valley cut and fill, barrier dam at valley mouth	Planned max. depth of fill is about 85 ft	Approx. 230 x 700 ft max.	Approx. 5 acres	Cut to 1 on 1 max.	3–10% natural slope	Gently down valley and terraced (proposed)	Diatomaceous shale and claystone	No aquifers	Unlined, in-place rock is liner	Unlined (but must be excavated to fresh rock	Final cover not yet designed	Final cover not yet designed
10	Belowground pits or trenches	22 ft	175 x 300 ft	1–2 acres	Approx. 1 on 1		2–9%	Clay, sandy clay, silty and clayey sand	Artesian (piezo. level at about 30 ft	4 ft in-place clay-rich soil or 3 ft compacted clay-rich soil	95% Standard Proctor	4 ft of compacted clay-rich soil	Same as liner

Table A1 (Continued)

Character/ Site No.	Leachate Collection System Distribution	Primary Waste Form	Other Waste Forms	Wastes Segregated ?	Waste Drum Placement	Waste Layer Thickness	Intermed. Cover (Fill) Thickness	Interm. Cover Composition and Placement	Handling of Liquids	Agents Used for Solidification of Liquid Wastes	Year Hazardous Waste Landfilling Began
1	Blanket of 8-in. washed gravel atop liner, drains to PVC pipe in trench, to concrete riser	Bulk solidified and drums of solidified wastes	Plastic drums, steel tanks, wood pallets, etc.	No	On edge (horiz.) Empty drums crushed	Approx. 2 ft	12 to 18 in.	Ripped, crushed native claystone spread in horizontal layers by D6 or equivalent	Decanted and solidified in landfill or solidified in drums. Bulk liquids solidified in landfill	Commercial adsorbents (Fuller's earth) and cement fly ash	1977
2	Radial network of 4-in. PVC drain pipe in 2 ft sandy soil blanket drains to concrete riser at center of cell	Bulk solidified and drums of solidified wastes	Sheet plastic, wood pallets, plastic drums, etc.	Yes	On end (vert.) Empty drums crushed	Approx. 3 ft	Approx. 2 ft	Ripped, crushed native claystone spread in horizontal layers by dozer smaller than D6	Bulk liquids solidified in landfill cells, liquids in drums solidified in drums	Fuller's earth (an adsorbent clay)	1978
3	1 ft blanket of crushed stone and graded filter with collection line at one end leading to concrete riser. Also vertical drainage ground riser	Steel drums	Plastic drums (fiberpaks), plastic bags, etc.	Yes	On end (vert.) Empty drums crushed	Approx. 3 ft	6 to 12 in.	Selected covers are spread by tracked vehicles	Solidified in drums	Selected for waste compatibility	--
4	6-in. PVC pipe laid along sides and bottom of pit every 100 ft, pipe covered with 6 in. of gravel	Bulk solidified liquids and bulk solids	10-15% steel drums	No	On end (vert.) Empty drums	Waste-adsorbent mixture spread in ½-1 ft lifts	Inter. cover not used	Inter. cover not used. Waste-absorbent mixture is advanced along a low slope when spread	Liquids solidified in place (in landfill) by solidifying agents	Cement kiln dust	--
5	6-in. thick layer of pea-gravel blankets bottom of trench. 6-in. PVC perf. pipe imbedded in blanket at center of trench, drains to concrete riser external to trench	Bulk solidified liquids and solid wastes	Plastic, wood, iron pipe, various containers, crushed drums	Yes	No intact drums	Approx. 15 ft (no layers, fill is advanced by end dumping on vertical face	No inter. cover	No inter. cover. Wastes and debris are mixed and end-dumped to advance a vertical face	Liquids mixed with native soil and spread into fill	Native soils	1980
6	4-in. slotted PVC pipe laid down on end slope and down center line on bottom of trench. Some crushed rock covers	Bulk solidified liquid and solid waste	Crushed drums	No	No intact drums	About 1 ft	No inter. cover	Solidified waste mixture is spread by dozers in thin lifts on gently sloping advancing front	Bulk liquids solidified in separate mixing pits by jetting of adsorbent to desired consistency, then moved to landfill	Cement kiln dust	Present owner 1980, previous owners 1976
7	None. Evaporation rate very high. Monitoring wells are maintained around landfills	Drums of solidified wastes. Drums total 90% of waste layers	Wood boxes, crates, transformer bodies, contaminated soil	Yes	On edge (horiz.) 2-3 layers at a time	4-6 ft, but varies across fill	6-in.	Native soils are spread by rubber-tired scrapers	Liquids mixed with adsorbent in the drums	Bentonite, fullers earth, cement kiln dust	1970
8	French drains along inside toe of slope, drain down hill to 18-in. steel riser, collection sump at barrier dam	Bulk solidified liquids, sludges	Steel and fiber drums, polluted soil	No	No intact drums yet. Empty drums are crushed, distributed into landfill	Approx. 1 ft	No inter. cover.	No inter. cover. Bulk wastes mixed with excavated clay shale and spread in thin lifts	Liquids mixed with excavated clay shale to soil consistency	Native excavated clay-shale	1968 under previous owner
9	Gravity drainage downslope to perf. PVC pipe at toe of barrier dam to gravel sump and metal riser at center of barrier dam	Drums of solidified wastes	Wooden crates of contaminated soil, transformers	Yes	On end in layers of 1-drum thickness	Approx. 3 ft	4 ft	Native soils, low-pressure dozers advance fill along 3-4 ft face	Liquids solidified in drums by waste producer. Older cells have buried liquid wastes	--	1972
10	Centrally located slotted PVC riser	Drums of solidified wastes. Drums total 50-75% of waste layer	Bulk wastes	--	On edge	--	--	--	Older cells contain buried liquid wastes. Now, liquids solidified with soil	Native soil	1972

the fill for burial. The waste layer thickness describes the waste layer separated by interim cover or fill layers of soils or other inert materials. Some landfills bury primarily bulk wastes, which are spread in thin or thick lifts and commonly for which no intermediate cover is used. Where intermediate cover is used its thickness and composition are described in the table. The method by which liquid wastes are stabilized, or solidified, and the agents used, are shown. The year in which the first hazardous wastes were buried in the facility is given where known. Many sites contacted in the study had a history of multiple ownership, many of which predate RCRA. Therefore, there are sometimes older fills onsite for which little information is available regarding contents or construction. The information shown in the table for Site No. 10 was not derived firsthand and is less complete than information for the other sites. A narrative description of Sites 1 through 9 follows.

Site No. 1

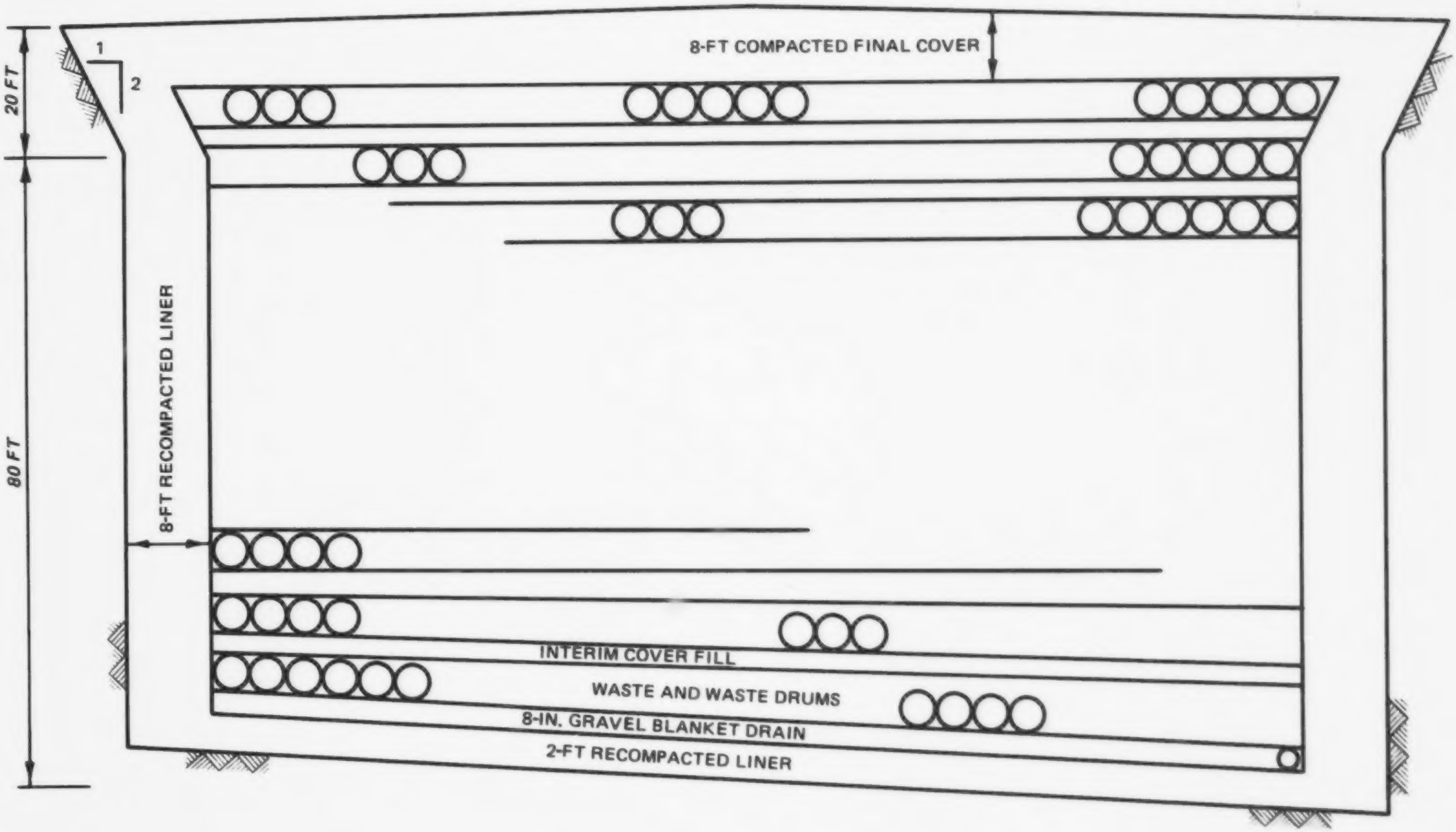
This facility is located in the eastern U. S. and occupies about 2400 acres of plant area. The owners consider the site ideal for hazardous waste landfilling because it is underlain by a considerable thickness of claystone and siltstone of low permeability and relatively high strength. The first hazardous wastes were buried at the site in 1977. The landfills are large pits excavated in the claystone to depths of up to 100 ft with near-vertical side slopes except for the upper 20 ft which is a remolded soil replacing weathered material and is cut back to 2V on 1H. The bottom of the pit is typically 300 ft square and is graded to slope to one side at about 5 percent. Earlier cells were only 30 ft deep. The landfills are single-cell, that is the wastes and waste containers may be placed anywhere within the large pit during filling operations and no berms or other dividers are used to subdivide the pit.

The pit is excavated to grade and a one-piece liner consisting of 2 ft of crushed native claystone is emplaced along the base and compacted with sheepsfoot rollers to specification. Compaction is specified at 95 percent Standard Proctor and is monitored. An 8-ft thickness of the clay liner is maintained against the sides of the pit as the filling progresses. The leachate collection system is an 8-in.-thick blanket of washed gravel emplaced atop the bottom liner, a perforated PVC collection pipe along the toe on the low side, and a 4-ft-diam concrete riser for access to collected leachate. Landfilled wastes seem to be divided evenly between drums and bulk solids and solidified liquids. Drums are placed on their sides (horizontally) and closely packed. An area of drums may abut an area of bulk wastes and other debris. The waste layer when completed is covered with 12 to 18 in. of excavated, stockpiled native claystone. The intermediate cover materials are spread with motorized scrapers and D6-equivalent bulldozers. Waste and intermediate cover are alternated to within 8 ft of the ground surface. The upper 8 ft of the pit is filled with crushed, remolded claystone in 1-ft lifts to the same specifications as the bottom liner, to form the final cover. The center of the final cover is crowned to produce an unspecified slope on the upper surface. Figure A1 illustrates the construction of a pit of Site No. 1 in cross section.

Bulk liquid wastes are solidified before burial by mixing them with absorbents such as cement kiln dust in temporarily isolated mixing cells within the pit. The mixture is then spread into the landfill. The resultant mixture is strong enough to support heavy tracked vehicles. Liquids in drums are solidified by adding a commercial absorbent, kaolinitic clay or "fuller's earth," to the drum contents. Drums are filled to within 5 percent full to prevent occurrence of voids. Empty drums and other containers are crushed before burial. Rain falling into the pit has to be considered contaminated and must be treated as liquid waste, i.e., it must be isolated and solidified before burial, which reduces available landfill space. Retention of rainwater is a common operational problem in pit-type lined landfills in regions of moderate to high rainfall.

Site No. 2

Site No. 2 is in the eastern U. S. and occupies approximately 268 acres of plant area. The first landfill was opened in 1978. The base levels of the pit-type landfills lie totally within a siliceous claystone, which when extracted and crushed produces an efficient commercial absorbent (fuller's earth). The absorbent properties of the excavated claystone make it ideal as a solidification agent for liquid wastes and, in the less pure form, as intermediate cover fill for landfill operations. The claystone formation is only 50-65 ft thick and the depth of the landfill pits are limited to 40 ft after 30 to 40 ft of sandy clay overburden is removed. A water-bearing sand underlies the claystone at a depth of 10 to 15 ft below the base of the excavated



8-FT COMPACTED FINAL COVER
1
2
20 FT
80 FT
8-FT RECOMPACTED LINER
INTERIM COVER FILL
WASTE AND WASTE DRUMS
8-IN. GRAVEL BLANKET DRAIN
2-FT RECOMPACTED LINER

Figure A1. Cross section of landfill of site number 1.

pit but artesian pressure places the piezometric surface 10 to 20 ft above the pit base. The typical pit is rectangular in plan, measures 200 by 500 ft at the base and the sides are cut to a 3 horizontal on 1 vertical slope. The landfill pit is divided into three cells by constructing earthen berms across the pit. The berms are reconstructed with each lift until the pit is closed and capped. The berms permit isolation of chemically or physically incompatible wastes, specifically organic, acid, and alkaline wastes. Wastes consist primarily of bulk solid and solidified materials and solidified waste in steel drums. Figure A2 illustrates the construction of a landfill for Site No. 2, in cross section.

The pit is excavated to grade, covered immediately to prevent drying and cracking, and a dual liner consisting of a 5-ft-thick layer of remolded, compacted clay overlain by a 30-mil-thick blanket of Hypalon, a fiber reinforced synthetic geomembrane, is installed. The 5-ft clay liner is compacted wet of optimum in 1-ft lifts with sheepsfoot rollers to a laboratory determined density that corresponds to a permeability to water of 10^{-8} cm/sec. The clay for the liners and cover is borrowed from overburden materials. Quality control of liner and cover compaction specs is maintained by a consulting laboratory. Permeability (k) to water is measured in a triaxial chamber on remolded compacted specimens back pressure saturated. Field permeability tests are not conducted on the clay liner but field density checks are made using a densitometer or balloon volumeter. A plasticity is chosen that will give the desired permeability of 1×10^{-8} cm/sec. The desired plasticity occurs at a dry density of 92-93 pcf and a water content of 25 to 30 percent. Optimum density of the compacted clay, obtained by standard Proctor compaction, is 112-113 pcf and occurs at a water content of 15 to 20 percent. The clay has a liquid limit of about 50 percent, a plastic limit of 21 to 29 percent and 84 to 85 percent passes the No. 200 sieve. The in-place water content of a typical laboratory sample was quoted as 28.5 percent, the saturation 93.3 percent, and the void ratio as 0.82. The specific gravity of the grains is 2.68. A vibratory roller is used on the final lift of the clay liner to provide a smooth surface for the geomembrane. A 2-ft-thick blanket of sandy, clayey overburden soil is spread atop the Hypalon liner to serve as a buffer to protect the liner and to assist the leachate collection system. A leachate collection system of 4-in.-diam PVC drain pipe is placed within the 2-ft sandy

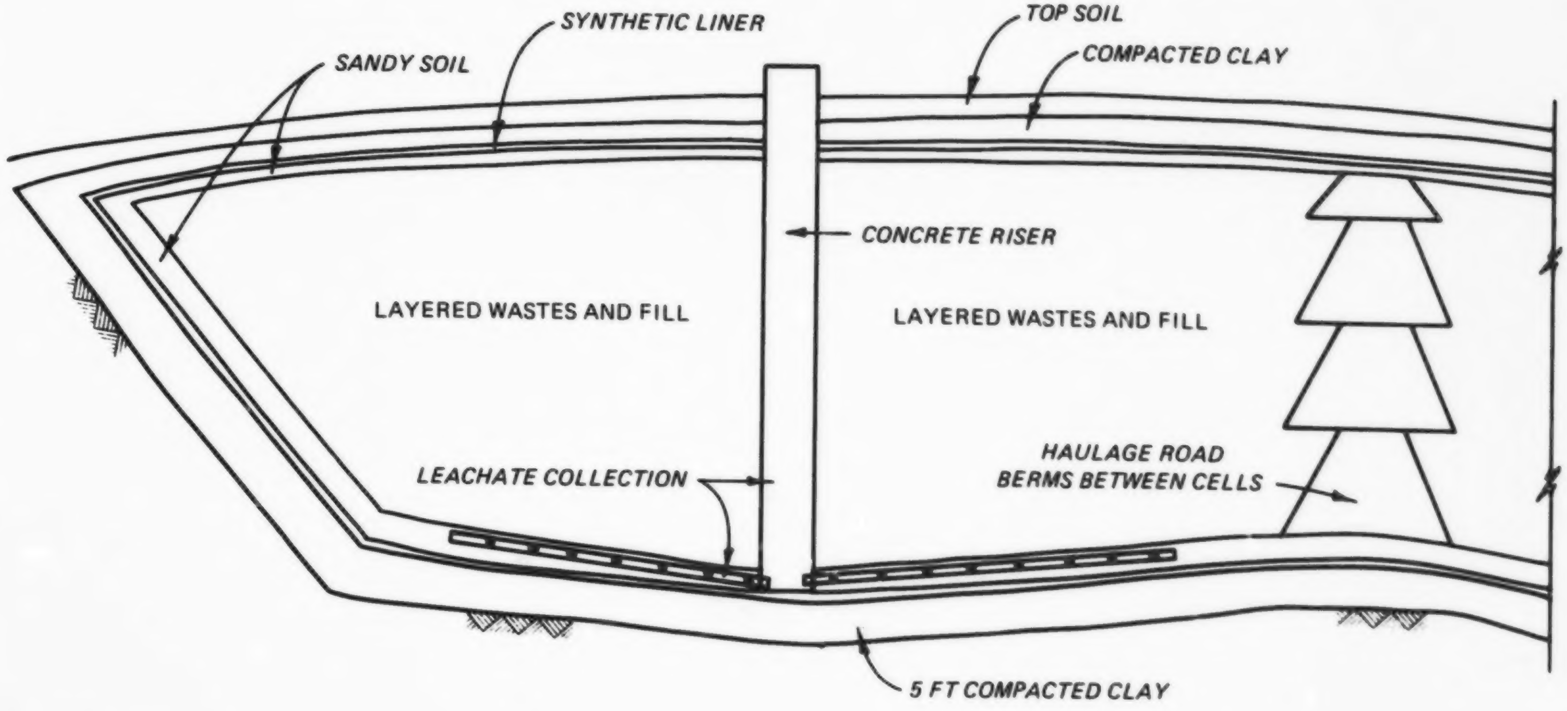
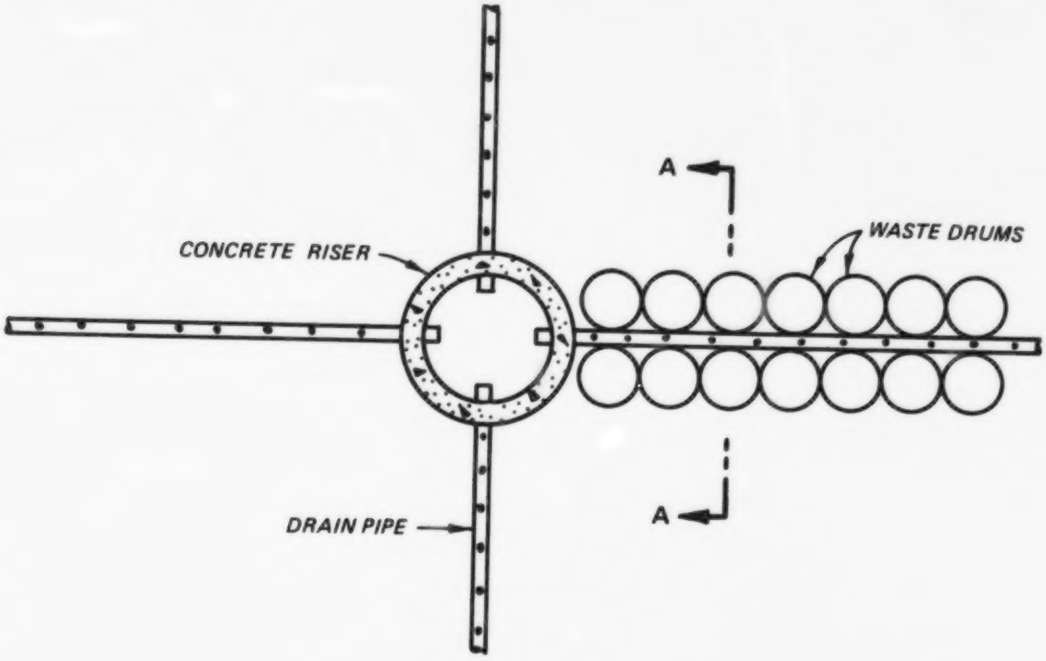

SYNTHETIC LINER
TOP SOIL
SANDY SOIL
COMPACTED CLAY
CONCRETE RISER
LAYERED WASTES AND FILL
LAYERED WASTES AND FILL
HAULAGE ROAD
BERMS BETWEEN CELLS
LEACHATE COLLECTION
5 FT COMPACTED CLAY

Figure A2. Cross section of landfill of site number 2.

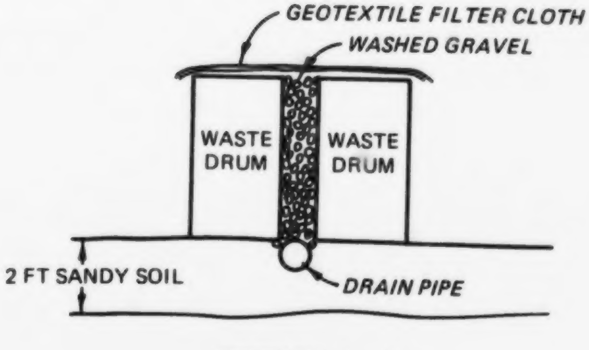
soil layer and leads to a 4-ft-diam concrete sewer pipe riser at the center of each cell. The concrete riser is carried upward as filling progresses by adding 5-ft sections of pipe. Figure A3 shows construction details of the leachate collection system. A row of waste drums is placed along each side of each collection pipe to protect the pipe. The slot formed between the drums is then backfilled with washed gravel. A geotextile, a 50-mil nonwoven fabric, is laid across the drum-gravel surface to prevent washing of fines into the gravel. Normal waste-fill procedures are then started.

The first layer of wastes, consisting primarily of steel drums and solidified wastes, is emplaced on the sandy layer, and then covered with about 2 ft of the crushed, dried "fuller's earth" absorbent. The absorbent is spread with rubber-tired front-end loaders and light crawler tractors so that it sifts down between the waste containers and completely covers the waste layer. The absorbent fill varies in particle size from dust (clay-sized) to perhaps 1/4 in. The operation observed probably results in some bridging of the fill over voids. Waste containers are closely stacked, however, and large voids probably are not created during filling of the cell. Waste drums are placed on end (long axis vertical). Waste and fill layers are alternated up to the top of the cell and the cells within the section are then capped. One ft of sandy clay is placed atop the last waste/fill layer. Twenty-mil PVC with a 30-mil factory-bonded Hypalon edging is then bonded to the Hypalon liner to envelop the cells. A 2-ft-thick blanket of clay is compacted atop the synthetic liner to the same specs as the liner clay. Finally 18 in. to several feet of topsoil caps the cells. The cap is grassed and settlement plates or supposed to be installed. To date, no settlement plates have been installed but were scheduled for installation. All wastes brought into the facility are weighed and classified and when added to the cell are mapped on a 3-axis system so that their positions are known.

All liquids handled by the facility, including those in containers and in bulk, are solidified by the addition of crushed and dried "fuller's earth" absorbent. Liquids in drums are treated within the drums or if the drums are full they are partially emptied into other drums and both drums of liquids then treated. Leaking or damaged drums acquired off-site or brought to the site are repackaged in 85-gallon "overpack" steel drums. Emptied drums are usually crushed along the long axis to a thickness of about 8 in.


A
WASTE DRUMS
CONCRETE RISER
A
DRAIN PIPE

PLAN


GEOTEXTILE FILTER CLOTH
WASHED GRAVEL
WASTE DRUM
WASTE DRUM
2 FT SANDY SOIL
DRAIN PIPE

SECTION A - A

Figure A3. Leachate collection system for site number 2.

Partially full drums are refilled with absorbent so that air space (void) is reduced. Bulk liquids are usually transported to the facility by tank truck. The trucks drive directly to the top edge of the pit where they discharge their loads into the appropriate cells by laying the discharge hose onto the pit slope and opening the valve. In the early stages of cell filling the hoses do not reach the bottom of the cell but discharge directly onto the 3 on 1 side slope. Associated erosion of the slopes in several places by gullying was observed during the site visit but erosion reportedly does not compromise the side liner. The liquids run into a pit within the cell where they form a pool that is solidified by addition of absorbent material. Most of the waste drums appeared to be in good condition but some were damaged, partially crushed, or punctured. Some sheet plastic, used to cover and line waste transportation trucks, is buried along with other waste. Wooden pallets are also observed in the waste fill. Larger containers, such as truck tank cars, are crushed and included occasionally in the cells in addition to the 55 and 85-gallon drums. Plastic drums are sometimes disposed of. The solidified bulk liquid wastes attain a consistency sufficient to support the wheeled and tracked earth moving vehicles that operate in the pits.

Site No. 3

The facility is located in the eastern U. S. The site was not visited for this study but information was obtained through correspondence with site personnel. The landfills are partially below grade but most of the volume of the fill is placed aboveground behind retaining dikes, and would probably be classified as surface impoundments by EPA. Early fills at the site were 1 to 2 acres in area and were capped and closed in 1978. A presently active area, or cell, is 3-5 acres and a planned cell will be 14 to 17 acres in size. The cells are excavated into glacial till and clay. A 10-ft-thick remolded clay liner is installed along the base and interior 1 on 1 slopes by compacting in 6-in. lifts to achieve a permeability to water of no more than 10^{-7} cm/sec. An 80-mil high density polyethylene (HDPE) geomembrane liner is then emplaced atop the clay and a buffer of 1 to 2 ft of additional clay is laid atop the geomembrane. The cell is divided into as many as 5 subcells by clay berms to allow segregation of wastes. The subcells isolate heavy metals, pseudometals (arsenic, antimony, bismuth, etc.), organics, flammable wastes, and toxic wastes. The subcell base is graded to slope toward an exterior berm at

2 percent, and a leachate collection system is installed. A 1-ft-thick graded stone filter blanket covers the base of the subcell and directs leachate (primarily rainwater) to a 42-in. concrete cylinder riser. During operations side riser pipes assist in removing leachate. Figure A4 diagrams a Site No. 3 landfill in section.

Wastes are primarily in steel drums. The first layer of drums is placed directly atop the leachate layer, the drums in upright (on-end, vertical) position. A 6- to 12-in. layer of intermediate cover is spread atop each waste layer as fill progresses. The composition of the intermediate cover varies with each subcell for waste compatibility, and may consist of clay, limestone, ashes, or specialized covers. The intermediate cover fill receives some compaction from the tracked vehicles used to apply it. The final cover consists of 3 ft of compacted remolded clay atop the last waste layer, followed by a HDPE geomembrane liner, about 18 in. of clayey soil and a 6-in. top layer of topsoil. The final cover surface slopes away from the center at 8 percent, as constructed.

All liquids, in drums and in bulk, are chemically analyzed and treated with absorbent or stabilizing agents the composition of which is determined by the chemistry of the waste. Classification of wastes also permits accountability and mapping of all wastes buried in the landfill.

Site No. 4

Site No. 4 is located in the south central U. S. near the Gulf Coast. The site covers 86 acres of which 50 acres are available as landfill. The landfills are pits excavated belowground in clays and silty clays with occasional lenses of silty sands. Each cell is approximately 3 to 5 acres in area, 50 ft deep, and has side slopes of 1V on 2.5H. The base of the cell slopes to one side. Cells are lined by placing 4 ft of remolded compacted clay-rich soil against the base and sides, using a sheepsfoot roller and placing in 6-in. lifts. The state requires compaction at 95 percent of Standard Proctor. Liners must have a permeability to water no greater than 10^{-7} cm/sec. In excavating the cells, a large pit area is excavated to grade and divided into smaller areas of cells by the use of temporary clay berms. In an active cell, therefore, three sides may consist of adjoining waste fill slopes, and the other side of the native soil cut slope. The temporary clay-soil berms protect the operating cell from contamination by the adjoining waste fill.

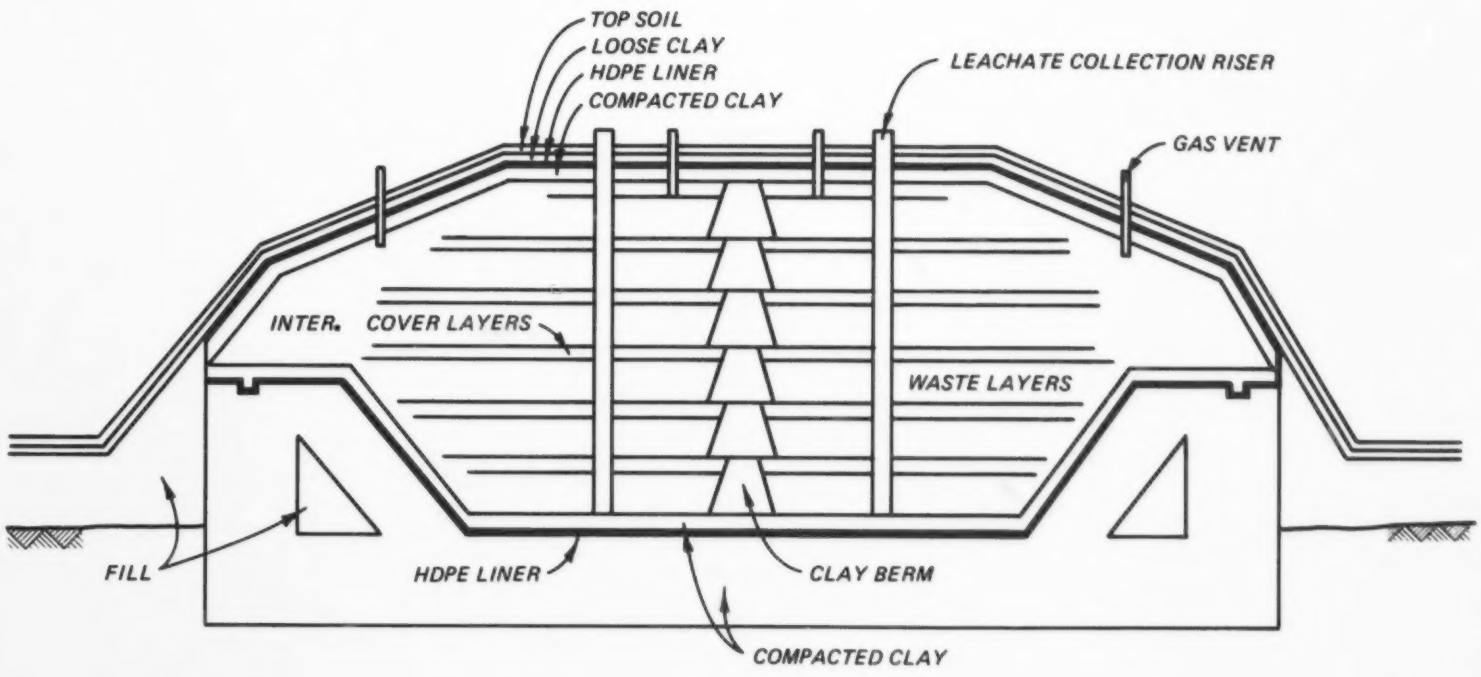

TOP SOIL
LOOSE CLAY
HDPE LINER
COMPACTED CLAY
LEACHATE COLLECTION RISER
GAS VENT
INTER.
COVER LAYERS
WASTE LAYERS
FILL
HDPE LINER
CLAY BERM
COMPACTED CLAY

Figure A4. Cross section of landfill of site number 3.

The leachate collection system consists of slotted 6-in. PVC pipe laid down every 100 ft along the side slopes from the ground surface down into the center of the cell. A granular soil layer is emplaced along each section of pipe along the base of the cell. Wastes are primarily bulk solids and solidified liquids. Drums comprise only an estimated 10 to 15 percent of the waste. Solidification is achieved by mixing cement kiln dust with the bulk liquids in mixing pits. The resulting mixture is spread along the working base of the cell in thin (6-in. to 1-ft) lifts and receives some compaction by D-5 and D-8 Caterpillar dozers. If steel drums of wastes are included in the fill there are no more than three stacks of drums vertically within any location of the cell and 2 to 3 ft of solid bulk wastes are placed between drum layers, with at least 5 ft of bulk waste between the lower drum layer and the cell base. Empty drums are crushed before being placed in the fill. A final cover is not planned for this facility because the site manager has applied for a permit to construct surface impoundments atop the existing landfill.

Site No. 5

The site is located near the Gulf Coast in the south-central U. S. The facility occupies about 450 acres most of which is dedicated to land farming, a method of disposing of Class II and milder wastes (Class I wastes are hazardous materials) by incorporating them into the topsoil with a disc harrow. Approximately 18 acres of the facility are currently used for below grade landfilling. Four active cells, or trenches, are being worked. Wastes, almost totally in bulk form, are segregated by type in different trenches: one for iron oxide catalyst, one for sludge (solidified), one for organics, and one for acid mixed in a stabilizing agent. This is a relatively small facility taking wastes from a few local suppliers. The first wastes were landfilled in 1980.

The landfill trenches are 15 ft deep, approximately 80 by 110 ft on the base and about 170 by 200 ft at the top, with 1V on 1.5H side slopes. The trenches are excavated in clays, silty clays, and silty sands. Water-bearing strata occur variably at a depth of about 25 ft but artesian pressure places the piezometric level at a depth of 3 to 4 ft below ground surface. An ancient sand-filled stream channel traverses the site and if intercepted by an excavated trench the sand is removed to a depth of a few feet and that area of the trench wall backfilled with clay-rich material. Alternately, no liner is required if 4 ft of in-place clay-rich soil exists in the cut trench walls and base. Clay-rich soil is defined by the state as having a water content 30 percent, a plasticity index (PI) of 15, and 30 percent passing the No. 200 sieve. A compacted liner of 3 ft of remolded clay-rich soil is emplaced prior to landfilling the trenches. The liner is compacted to 95 percent Standard Proctor density. A consulting engineering laboratory monitors site construction requirements with subsurface exploration techniques and runs field density tests on compaction. Typical test results for liner soils are: light gray to red clay, Standard Proctor compaction maximum dry density 94.6 pcf, optimum water content 26 percent. Typical in-place conditions of the clay-rich soil were 24.8 to 31.0 percent water content and 87.0 to 99.7 pcf, or 90.2 to 103.4 percent Standard Proctor. Laboratory constant head permeability tests on back-saturated samples of the clay-rich strata yielded permeability to water of 10^{-8} to 10^{-9} cm/sec.

Leachate collection is achieved by emplacing a 4-in. slotted PVC pipe in the center of the trench in a 6-in.-thick blanket of pea gravel covering the trench base. The trench base slopes toward one end where a right-angle bend in the 4-in. PVC pipe directs leachate to a riser and sump. Figure A5 diagrams a typical trench in section. The bulk solidified wastes and other solid debris are deposited in the trenches by end dumping over a vertical face 15 ft high which is advanced along the trench axis toward one end. A cover of 4 ft of clay-rich soil caps the trench.

Site No. 6

The site is located near the Gulf Coast in the south central U. S. The facility occupies about 440 acres most of which is dedicated to landfilling operations. Part of the site originally was operated as a hazardous waste landfill under different owners but merged with the current owners and expanded in 1981. The landfills are individual pits or trenches 12 to 17 ft deep excavated in silty, sandy clay generally less than 20 ft thick and underlain by silty and sandy soils. The piezometric level is at about 2-3 ft depth (belowground surface). The trenches are typically 100 ft wide by 400-500 ft long at the top with 1 on 1 side slopes. The trench bottom slopes toward the axis of the trench. A liner is not required as long as there is 4 ft of in-place clay-rich soil (see definition for Site No. 5) in the trench, walls and floor. The leachate collection system is a single 4-in. slotted PVC pipe

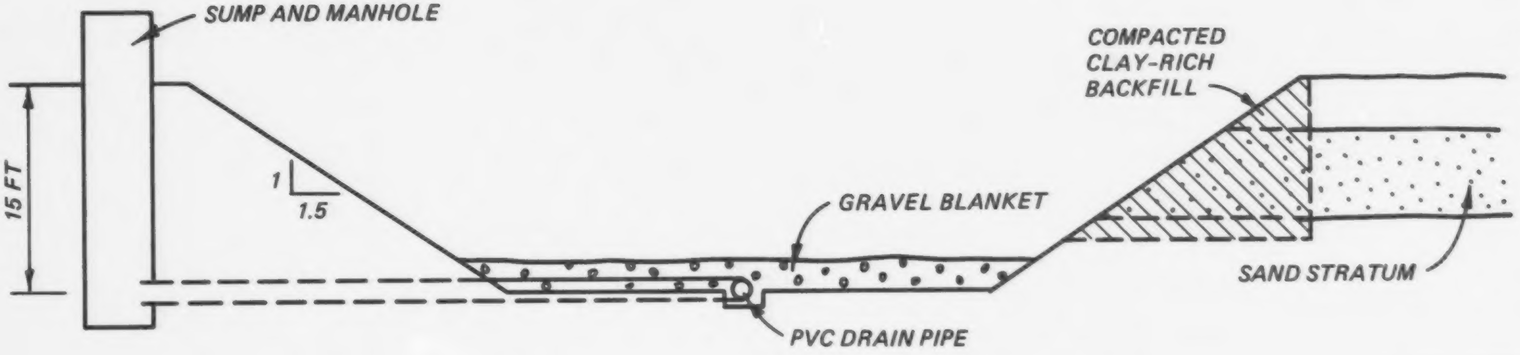

SUMP AND MANHOLE
15 FT
1
1.5
GRAVEL BLANKET
PVC DRAIN PIPE
COMPACTED
CLAY-RICH
BACKFILL
SAND STRATUM

Figure A5. Cross section (end view of trench of site number 5).

laid down the center on the bottom of the trench and up the end or side slope to aboveground. The pipe is covered with a variable thickness and amount of crushed rock.

Most of the waste is in bulk solid and solidified liquids. No intact steel drums are buried, but empty crushed drums are placed in small quantities. The facility incorporates a jet mixing technique to stabilize liquids. Liquids are loaded into a mixing pit and a tank truck injects Portland cement kiln flue dust at high pressure and velocity through a hose at the bottom of the mixing pit. Mixing and absorption appear to be quite complete with the method. The solidified wastes have a consistency resembling silty soil when placed into the burial trench. Bulldozers equipped with pyramidal treads for better compaction distribute the wastes along the long axis of the trench toward one end along a low sloping waste face. Final covers are not planned because the owners will apply for a permit to construct waste impoundments atop the existing landfills. In connection with the impending construction of embankments for the aboveground impoundments, a consultant conducted stability analyses on the proposed embankments and a consolidation analysis of the waste fills and in-place soils. The results of the analyses indicated that the mixture of Class I (hazardous) wastes and flue dust was stronger than the unmixed Class II wastes. The hazardous waste/flue dust mixture was less compressible than the stiff natural clay-rich soil with respect to primary consolidation.

Site No. 7

This site is located in the desert southwest. The facility's hazardous waste disposal landfills have been in operation since about 1970. The plant occupies 80 acres with 18 acres dedicated to chemical waste disposal. Disposal is in large pits divided into cells by berms of native soils. The pits are 50 ft deep, excavated in a horizontally bedded clay 90 ft thick below the pits that appears to be derived from volcanic ash falls. The upper several feet of strata are bedded clayey sands and gravels. The site managers consider the in-place clay a natural liner, and measured permeabilities to water are 10^{-7} to 10^{-9} cm/sec. Ground water is over 300 ft deep. Evaporation in the desert climate far exceeds precipitation. The active pit observed was 540 ft square with near-vertical side slopes. The pit was divided into four cells of unequal sizes for the segregation of acid, alkaline, organic, and PCB wastes.

The facility installs no leachate collection system in the pits but maintains monitoring wells around the site. At the current rate of filling the active cell is expected to take 12-14 years to fill.

Most of the waste is buried in steel drums, which account for an estimated 90 percent of the waste containers. Some bulk waste and other containers including wooden boxes and crates and transformers are also buried. Drums are placed on edge (horizontally) in stacks two or three drums deep. Six inches of soil (intermediate cover) separates each drum stack from the next higher stack. Some compaction of the intermediate cover is achieved by the rubber-tired motorized scraper used to spread the cover. Several tiers of wastes may be placed in one part of the pit before the adjacent area is used, and therefore the pits cannot be considered as being horizontally layered with respect to waste placement. Liquids (paints, sludges) in containers were buried in earlier pits prior to 1980, but no free liquids have been buried subsequently. The high evaporation rate at the site helps reduce the liquid content as the pit is filled. Liquid wastes are stabilized with several agents including cement flue dust, bentonitic clay, and fuller's earth. Fill proceeds to within 3 ft of ground level, then a cover of the excavated clay strata is applied and crowned 2 ft at the center for a total cover thickness of 5 ft at the center and 3 ft at the pit edges, which yields a cover slope of less than 1 percent.

Site No. 8

This site is located on the west coast in arid to semiarid climate (evaporation is approximately five times precipitation). The facility occupies approximately 280 acres with a 1900 acre buffer of land surrounding the working portion of the site. The facility incorporates holding ponds for liquid wastes and landfills for burial of solid hazardous wastes. The landfills are positioned in dry valleys between hills, the mouth of the valley dammed to create an impoundment. This facility is not a true landfill but should probably be classified as a hybrid between landfill, surface impoundment and wastepile. The landfill area is excavated down to fresh rock (marine siliceous siltstone to claystone or clayshale with some sandstone), cut to 1 on 1 side slopes, and then lined and filled. A perched water table exists beneath the site but is insignificant as an aquifer. The site has had at least two owners prior to its present ownership. The presently active landfill was started in 1979. Earlier ownership dates at least to 1968.

The liner is 2 ft of compacted remolded clay from the claystone subgrade. The liner is compacted with a special compactor with cleated feet to a desired permeability to water (measured typically 10^{-8} to 10^{-10} cm/sec). The leachate collection system consists of french drains installed along the inside toe of the cut and leading down-valley to a collection sump and 18-in. metal riser at the center of the barrier dam. As the fill proceeds upward the fill surface is terraced back toward the head of the valley and a new riser and leachate system installed at the new level. Figure A6 diagrams the fills in profile and plan.

Wastes almost totally have been bulk solidified liquids but some burial of drums is planned. Wastes are dumped over the edges of the fill and mixed with sufficient clayey material moved in from the edges of the valley to stabilize the liquids. The material is then spread into the fill in thin lifts by a bulldozer. The waste surface is then compacted to a reported 80 percent of Standard Proctor by the special compactors. Typical wastes received are paint residues, sludges, and metal-contaminated soil. Some solid debris such as fiber drums, minor paper and plastic debris, and wooden pallets are also included occasionally. An extensive system of runon-runoff drainage ditches is constructed around the fills to divert rainwater from the fill surface. The planned depth of the landfill before closure is about 100 ft. The final cover has not yet been designed.

Site No. 9

This facility is also located on the west coast in an arid-semiarid climate. The facility operates holding ponds and lagoons for liquid wastes (chiefly oil field related wastes) and recently (1978) began landfilling solid hazardous wastes. The plant occupies 250 acres and is surrounded by a buffer of plant-owned land of approximately 4300 acres. This facility like Site No. 8 also operates by filling in dammed valleys. The natural valleys are excavated to fresh rock, a diatomaceous (siliceous) shale and claystone, the side slopes graded to about 1 on 1, a clay barrier dam installed at the lower end, and the valley filled. The in-place material is of sufficiently low permeability to water (1 to 3×10^{-8} cm/sec and 78 percent passing the No. 200 sieve) that presumably no further lining is required to retain leachate. The claystone is 500 to 1000 ft thick at the site and there are no known aquifers below it. The natural down-valley slopes of the landfill areas are 3 to

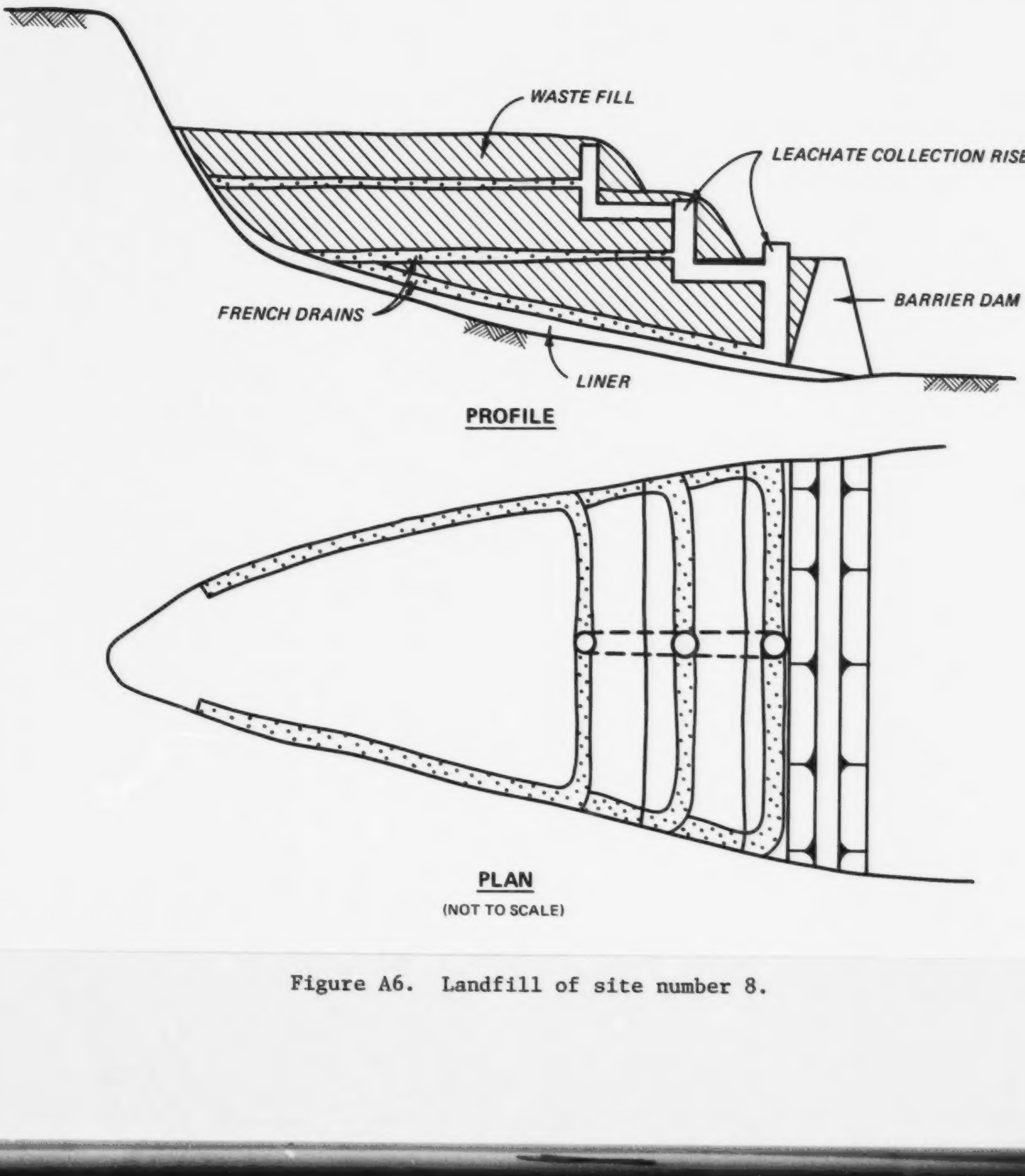

WASTE FILL
LEACHATE COLLECTION RISERS
BARRIER DAM
FRENCH DRAINS
LINER
PROFILE
PLAN
(NOT TO SCALE)

Figure A6. Landfill of site number 8.

10 percent. The 12-ft-thick barrier dams are constructed with care by compacting clay in lifts and keying about 4 ft into fresh rock. Leachate collection is by gravity drainage down valley to a perforated PVC pipe in a gravel curtain against the landfill side of the barrier dam, the pipe sloped to a central collection sump with riser. There are five separate landfills that vary in capacity from 47,000 cu yds to 172,000 cu yds. The maximum planned depth before closure for the largest landfill is about 85 ft.

Approximately 90 percent of the landfilled wastes are in steel 55-gallon drums. The drums are placed in single layers, closely and carefully stacked on end across the landfill surface. Each waste layer is separated from the next higher layer by 4 ft of crushed native diatomaceous fill as the intermediate cover. The site managers estimate that a completed fill will contain 73 percent of inert intermediate cover material and only 27 percent waste material. Wastes are segregated by reserving each landfill for one kind of waste. The fills are separated by several tens of feet of inplace claystone. The separate landfills are for solid PCB's, solvents/pesticides, heavy metals/sludges, caustics/cyanides, and acids. Figure A7 diagrams the largest landfill (the solvents/pesticides fill). The PCB landfill contains many large wooden crates approximately 3-4 ft square containing contaminated soil. Electrical transformer bodies are also buried. Liquid wastes in drums are solidified by the producer before delivery to the landfill. Vermiculite (an expanded mica) reportedly is a common solidifying agent. The final cover has not been designed for these landfills.

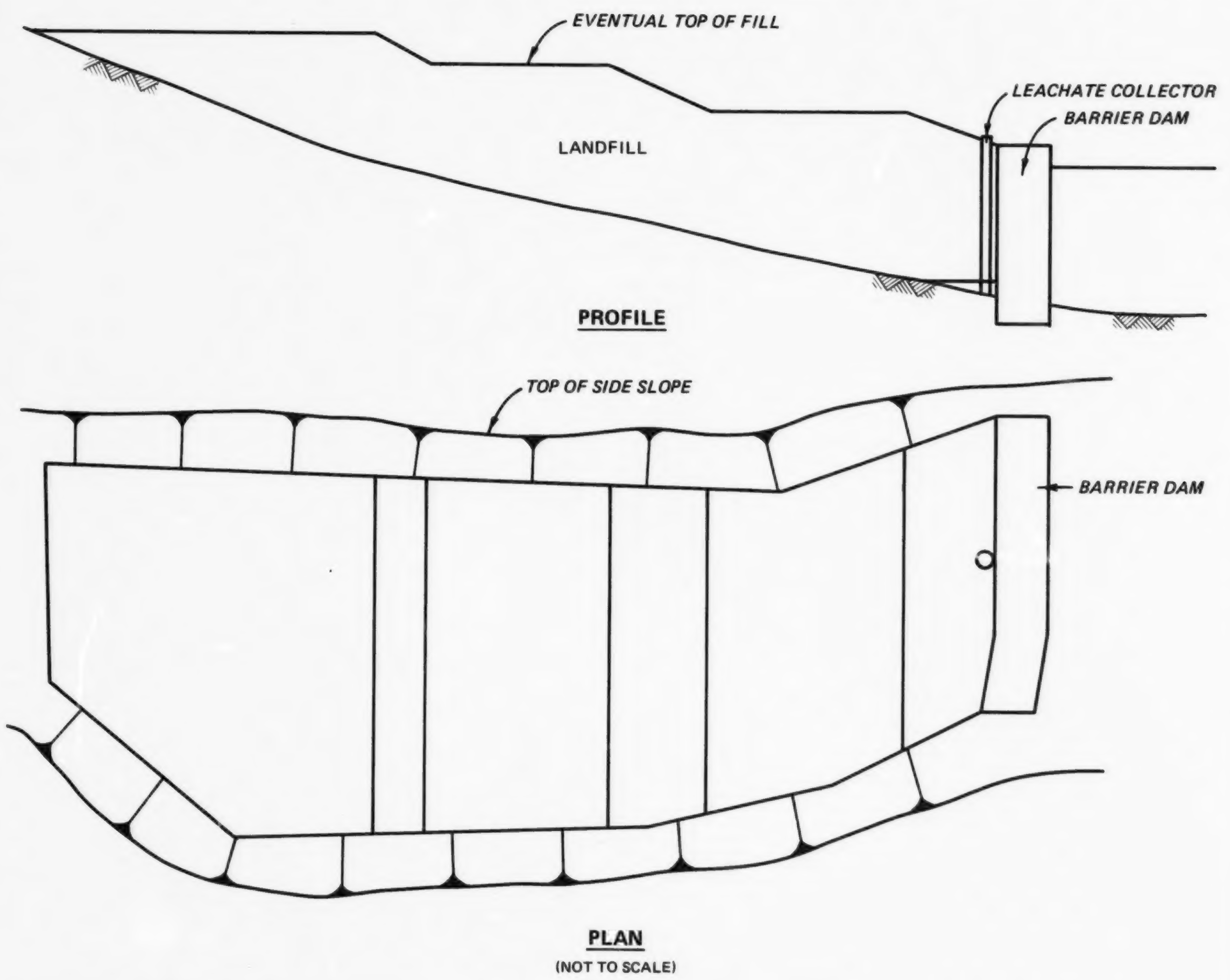

EVENTUAL TOP OF FILL
LEACHATE COLLECTOR
BARRIER DAM
LANDFILL
PROFILE
TOP OF SIDE SLOPE
BARRIER DAM
PLAN
(NOT TO SCALE)

Figure A7. Landfill of site number 9.

APPENDIX B

DERIVATIONS OF EQUATIONS FOR YOUNG'S MODULUS

(1) Young's modulus of drum subjected to uniform external pressure.

The assumption is made that a drum lying on its side will be subjected to a uniform pressure ΔP and that

$$(U)_{r=b} = \frac{-b\ \Delta P}{E} \left[\frac{a^2 + b^2}{b^2 - a^2} - \nu\right] \tag{1}$$

where

$(U)_{r=b}$ = radial deformation of the drum at radius b.

b = outer radius of the drum (= 11.175 in).

a = inner radius of the drum (= 11.125 in).

E = Young's modulus of the drum material (steel, $E = 30 \times 10^6$ psi).

ν = Poisson's ratio of drum material (steel, $\nu = 0.29$).

A unit thickness will be chosen so that the initial volume $V_i = \pi r^2$. If the final volume is $V_f = \pi(r + \Delta r)^2$ then the change in volume of the system neglecting higher order terms is

$$\Delta V = V_f - V_i = \pi\ (2r\ \Delta r) \tag{2}$$

and

$$\frac{\Delta V}{V} = \frac{2\pi\ r\Delta r}{\pi\ r^2} = \frac{2\Delta r}{r} \tag{3}$$

which becomes by substituting in equation (1)

$$\frac{\Delta V}{V} = \frac{2\Delta P}{E} \left[\frac{a^2 + b^2}{b^2 - a^2} - \nu\right] \tag{4}$$

and if one dimensional compression is assumed, the modulus of the drum, E_D is

$$E_D = \frac{\Delta P}{\left[\frac{\Delta V}{V}\right]} = \frac{E}{2\left[\frac{a^2 + b^2}{b^2 - a^2} - \nu\right]} \tag{5}$$

which becomes upon substitution

$$\begin{aligned} E_D &= 67352 \text{ psi} \\ &= 9.7 \times 10^6 \text{ psf} \end{aligned} \tag{6}$$

(2) Composite Young's modulus of soil/drum configuration for drums on their sides.

The assumption is made that the two-component system (the drum and soil, see Figure 20) will compress hydrostatically under pressure, i.e., the bulk modulus of the system can be computed from

$$K = \frac{\Delta P}{\left[\frac{\Delta V}{V}\right]} \tag{7}$$

where

ΔP = the increase in pressure applied to the system.

$\frac{\Delta V}{V}$ = volumetric strain of the system.

For the assumed condition of one dimensional compression, the bulk modulus, K , is equal to the Young's modulus,

$$K = E = \frac{\Delta P}{\left[\frac{\Delta V}{V}\right]} \tag{8}$$

The change in volume of the drum as a result of a change in pressure is equal to

$$\Delta V_D = \frac{V_D\ (\Delta P)}{E_D} \tag{9}$$

Similarly, the change in volume of the affected soil is

$$\Delta V_s = \frac{D^2\ (1/2 - \pi/8)\ \Delta P}{E_s} \tag{10}$$

where

D = drum diameter.

E_s = Young's modulus of the soil.

The total change in volume of the system is therefore

$$\Delta V_{TOTAL} = \Delta V_s + \Delta V_D \tag{11}$$

and

$$\Delta V_{TOTAL} = \frac{V_D\ \Delta P}{E_D} + \frac{D^2\ (1/2 - \pi/8)\ \Delta P}{E_s} \tag{12}$$

The volume of the drum is $\pi\ D^2/4$ and the total volume of the system is D^2 for unit thickness. Therefore, equation (12) reduces to

$$\frac{\Delta V_{TOTAL}}{V_{TOTAL}} = \Delta P \left[\frac{\pi}{4E_D} + \frac{(1/2 - \pi/8)}{E_s} \right] \tag{13}$$

which when combined with equation (8) yields

$$E_{composite} = E_T = \frac{4E_D\ E_s}{\pi\ E_s + 4E_D\ (1/2 - \pi/8)} \tag{14}$$

(3) Composite Young's modulus of soil/drum configuration for drums on end.

The assumption is made that for the drums standing upright (on end), a uniform pressure ΔP is applied over the top surface of the drum and that the contents will initially contribute no stiffness to the system. Therefore the total force applied to a drum is

$$F = A_T\ \Delta P \tag{15}$$

where A_T is the total area of the top of the drum and equal to $\pi\ b^2$. The deflection, δ, of the drum is

$$\delta = \frac{FL}{A_s\ E} \tag{16}$$

where

L = drum length

E = Young's modulus of drum material (for steel, $E = 30 \times 10^6$ psi)

A_s = area of the material of drum = $\pi\ (b^2 - a^2)$

b = outer drum radius = 11.175 in.

c = inner drum radius = 11.125 in.

Therefore

$$\delta = \frac{A_T\ \Delta PL}{A_s\ E} \tag{17}$$

But the strain in the drum is the ratio $\frac{\delta}{L}$ and the applied stress is ΔP. Therefore the effective Young's modulus of the drum is the ratio

$$E_D = \frac{\Delta P}{(\delta/L)} = \frac{A_s\ E}{A_T} \tag{18}$$

which yields

$$E_D = 3.86 \times 10^7 \text{ psi} \tag{19}$$

when appropriate values are substituted.